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Influence of hydrothermal factors on a coniferous forest canopy in the semiarid alpine region of Northwest China

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Analyzing the physiological response of trees to climate change in the Qilian Mountains region is key to studying the impact of global change on forest ecosystems in the semiarid alpine region of Northwest China. The leaf area index (*LAI*) of the canopy of a forest is an important input parameter for simulating carbon and water cycles in forest ecosystems. Studying the relationship between *LAI* and environmental factors can provide a scientific basis for accurately describing the structure, function, and ecohydrological processes of forest ecosystems and theoretically guide for sustainable management of water conservation in forests. Methods: In this study, the *LAI* of *the Picea crassifolia* canopy was monitored for 2 years (2015–2016) by field observations, and its dynamic changes were analyzed. The relations between *LAI* and air temperature (*AT*), precipitation (*P*), soil temperature (*ST*), and soil water content (*SWC*) were studied using Pearson's correlation and multiple regression analyses. The results were as follows: seasonal variations in *LAI* showed a single-peak curve, which first increased, reached a maximum, remained relatively stable, and then decreased. The maximum value was 4.02 and 4.18 relatively observed in mid-August 2015 and 2016. The *LAI* of the *P. crassifolia* canopy in different months was positively correlated with *AT* and *P*. It was correlated between the *LAI* of the canopy with ST_{40-60} in May and June ($p < 0.05$) and was also highly positively correlated between the *LAI* of the canopy with ST_{60-80}, ST_{mean}, and SWC_{60-80} in July and August ($p < 0.01$). There was a positive correlation between the *LAI* of the canopy with SWC_{0-60} and SWC_{mean} in July and SWC_{0-60} and SWC_{mean} in August ($p < 0.05$). The *LAI* of the canopy was affected by *AT* and *ST* in May and July, *AT* and *P* in June, *P* in August, and *P* and *ST* in September. Our study implied that the rapid increase period of the *LAI* of the canopy was from late May to early July. The *LAI* of the canopy was more influenced by temperature and water in July and August. In addition, the *LAI* of the canopy has significant seasonal variation although it is evergreen coniferous tree species.

KEYWORDS

leaf area index, air temperature, soil temperature, precipitation, soil water content, Qilian Mountains

1. Introduction

Leaf area index (*LAI*), the ratio of the surface area of a plant leaf to the surface area of land *LAI*, is used to quantitatively describe changes in leaf growth and density at the community level (Watson, 1958). *LAI* is an important input parameter for simulating the carbon and water cycles in forest ecosystems (Weiss et al., 2004; Wang et al., 2005);

(Bequet et al., 2011) and is the key factor in explaining the variation in the net primary productivity of aboveground vegetation (Leuschner et al., 2006; Kinane et al., 2022), which is an important factor in describing the structural characteristics of forest canopies. It controls many physiological and ecological processes within forest ecosystems, such as plant photosynthesis and transpiration, canopy interception of precipitation, and exchange of matter and energy between the atmosphere and canopy (Dermody et al., 2006; Liu et al., 2013). *LAI* is closely related to ecological processes in forests, and accurate determination of seasonal changes in *LAI* is conducive to simulating the response of vegetation to climate change and predicting forest growth status (Liu, 2015). *LAI* plays an important role in studying energy cycles of the ecosystem at the forest stand, landscape, and regional scales.

At present, the methods to measure forest *LAI* include the indirect measurement method and the direct measurement method (Bréda, 2003; Cerný et al., 2020). The former is simple and convenient; however, its accuracy of measurement must be calibrated. However, some optical instrument methods based on radiometric measurements need to assume uniform canopy, random leaf distribution, and elliptical leaf angle distribution, such as *LAI*-2000, while Tracing Radiation and Architecture of Canopies (TRAC) can effectively address the agglomeration effect by measuring the agglomeration index and without needing to assume a random leaf distribution in space (Chen, 1996; Zhao et al., 2009a; Behera et al., 2010; Cerný et al., 2020). The latter technology is mature and accurate, and its measured value is usually considered a real *LAI*; however, it is time-consuming, laborious, and destructive (Yan et al., 2019; Cerný et al., 2020; Fang, 2021). Optical instruments mainly include digital hemispherical photography, *LAI*-2000/2200 plant canopy analyzer, *TRAC*, CI-110 *LICOR* DEMON, and other equipment, among which digital hemispherical photography and *LAI*-2200 plant canopy analyzer are widely used to simultaneously observe the structural parameters of the canopy at different zenith angles (Behling et al., 2016; Fang et al., 2021). Direct measurement methods mainly include the destructive sampling method (Chason et al., 1991), the allometric growth equation method (Vyas et al., 2010), the oblique point sampling method (Wilson, 1960), and the litter method (Sprintsin et al., 2011).

The leaf area index is affected by several factors and exhibits varying degrees of temporal and spatial heterogeneity (Luo et al., 2011). The relationship between *LAI* and climatic factors (temperature, precipitation, and soil moisture) can efficiently reflect the interactions between vegetation and the environment and is suitable for studying the ecohydrological processes under climate change (Huang et al., 2016; Karimi et al., 2020; Kinane et al., 2022). Li et al. (2012) used a simple biological model, the SiB2 method, to calculate *LAI* and to study the annual and interannual variations in different vegetation cover types of *LAI* in the Poyang Lake Basin and their relation with precipitation and air temperature (AT). They highlighted that the responses of *LAI* to precipitation and air temperature have, respectively, a time lag of 3 months and 1 month in the annual variation, and the interannual variation of *LAI* is mainly affected by the precipitation between May and July (Li et al., 2012). Wang et al. (2008) analyzed the influence of hydrothermal conditions on vegetation *LAI* in the Qinghai–Tibet Plateau at temporal and spatial scales using remote sensing data and showed that *LAI* is correlated with temperature, soil moisture, and precipitation. Shao and Zeng (2011) compared potential *LAI* simulated by the dynamic vegetation model (CLM3.0-DGVM) with *LAI* derived from moderate-resolution imaging spectroradiometer (MODIS) and analyzed the spatial and temporal relations between *LAI* of different plant functional types on the current different types and climatic factors on the interannual scale. In addition, studies on *Hippophae rhamnoides Linn* and *Caragana intermedia* on the Loess Plateau indicated that *LAI* increased rapidly when precipitation and the water supply were sufficient, leading to a significant increase in the total amount of transpiration (Guo et al., 2007). However, an analysis of the US East Texas *Pinus taeda* stand canopy showed no significant relation between *LAI* and actual evapotranspiration ($r^2 = 0.06$) (Hebert and Jack, 1998), and plants from different biomes tended to grow relatively small leaves in arid environments to reduce the total leaf area, thereby reducing transpiration (Meier and Leuschner, 2008). In general, the main factors affecting vegetation *LAI* are temperature, water, and species.

Several studies have been conducted on vegetation *LAI* measurement methods and dynamic spatial and temporal (seasonal and interannual dynamics) changes in *LAI*; however, the relation between vegetation *LAI* and hydrothermal factors is not well understood. In particular, the relations between *LAI* of *P. crassifolia*, soil temperature (*ST*), and soil water content (*SWC*) in the Qilian Mountains of Northwest China are largely unexplored. Therefore, this study investigated the influence of hydrothermal factors on coniferous forest canopies in the semiarid alpine region of Northwest China. We monitored air temperature(*AT*), precipitation, *ST,* and *SWC* in the study area from 2015 to 2016 in this study. The objectives of this study are as follows: (1) to observe accurate monthly *LAI* dynamics using an *LAI*-2200C in coniferous stands; (2) to estimate the maximum stand *LAI* within the growing season indirectly using an *LAI*-2200C; and (3) to study the relation between *LAI* and *AT*, *P*, *ST,* and *SWC* in the Qilian Mountains.

2. Materials and methods

2.1. Study area

The study area is located in the Xishui Forest Area of the Qilian Mountains Natural Reserve. The geographical coordinates are approximately between 38°32′-38°33′ N and 100°17′-100°18′ E. These areas have the climate of alpine mountain forest grassland, with an annual *P* of 290–468 mm. The rainy season is mainly distributed from May to September, accounting for ~85% of annual *P*. The climatic characteristics were an average annual evaporation capacity of 1,082.7 mm, an annual average temperature of −0.6 to 2.1°C, and an annual average sunshine of 1,895 h. The average daily solar radiation intensity in 2015 and 2016 was 79.2 W·m^{-2}·d^{-1}.

P. crassifolia is distributed in patches on shady and semi-shady slopes at altitudes of 2,500–3,300 m. The sunny slope is dominated by grasslands with scattered Sabina przewalskii and shrubs. The herbs mainly include *Carex lancifolia*, *Stipa purpurea, Agropyron cristatum*, *Leontopodium longifolium*, *Taraxacum monogolicum*, *Potentilla bifurca*, and *Pedicularis*. The shrubs in the basin mainly include alpine shrubs such as *Caragana tangutica* and *Berberis diaphana Maxin*. Under the forest, moss is more developed; however, a few species, mainly *Abietinella abietina,* are scattered with *Bryoerythrophyllum tecurvirestrum* and *Tortula longimcronata*.

2.2. Sample plots

Three pure forest sample plots with *P. crassifolia* (25 ×25 m) were selected to observe the *LAI* of *P. crassifolia* in the study area in the growing season from May to October in 2015 and 2016 at an altitude of 2,700 m (38°33′14.8″ N, 100°17′5.4″ E). The selected plots were pure forests containing *P. crassifolia*, which originated from a natural secondary forest belonging to semi-mature forests. The horizontal distance between the three sample plots was ∼50 m. Height and diameter at the breast of all trees with a diameter at breast height > 5 cm were measured with a wooden ruler in the sample plots during the stable growth period in 2016. The surveyed parameters included tree height, diameter at breast height, crown width, canopy closure, and forest age.

2.3. *LAI* measurement

An *LAI*-*2200C* plant canopy analyzer (LICOR, Lincoln, Nebraska, USA) was used to measure the canopy *LAI* of *P. crassifolia* sample plots every 10 days from May to October in 2015 and 2016. The measurement frequency was appropriately increased because of the rapid growth and change in the new branches of *P. crassifolia* at the beginning of the growing season, which means, the *LAI* of *P. crassifolia* canopy was measured every 6 days in May. A total of 25 points were measured in each sample plot according to a fixed S-shaped route, and the average value was taken as the characteristic *LAI* of the canopy layer of the sample plot. To ensure that the canopy layer outside the sample plot was not detected, the distance from the observation point to the upper and lower edges of the sample plot was 3 m (slope length), and the left and right edges were 2.5 m each. Two *LAI*-*2200C* plant canopy analyzers were used for synchronous and accurate measurement; one was placed in an open space outside the forest to measure the *A* value, and the other was placed in the sample plot to measure the value under the canopy (*B* value). A camera (*D*80, Nikon) was used to obtain hemispherical images of the vegetation canopy and to calculate the *LAI* of the forest canopy (Chen, 1996; Zhao et al., 2009a).

2.4. *AT* and *P* measurement

We used an automatic weather station (Campbell Scientific, Inc., Logan, Utah, USA) above 15 m height in the third sample plot to continuously obtain the data of *P* (P/mm) with a rain gauge (TE525MM, Campbell Sci., Logan, USA), solar radiation intensity ($R_s/w{\cdot}m^{-2}$) with a solar radiation sensor (Li200X, LICOR, Lincoln, Nebraska, USA), *AT* (T/°C) with a temperature sensor (HMP115A, Campbell Sci., Logan, USA), and relative humidity of the air (RH/%) with a humidity sensor (HMP45A, Campbell Sci., Logan, USA). The interval of data collection was 10 min.

2.5. *ST* and *SWC* measurement

A HOBO U30 sensor (Campbell Scientific, Inc. Logan, Utah, USA) was installed in 0–10, 10–20, 20–40, 40–60, and 60–80 cm soil layers in each different sample plot to monitor *ST* (°C) and *SWC* ($m^3{\cdot}m^{-3}$). The interval of data collection was 30 min.

2.6. Data processing

A correction coefficient was required to adjust the measured *LAI*, which was low owing to the clustering effect of the coniferous forest. The measured *LAI* value used to calculate the correction coefficient was 0.996 (L_e). The aggregation coefficient (Ω_E) of *P. crassifolia* forest was 0.93 measured by Tracing Radiation and Architecture of Canopies (TRAC, Canada Center For Remote Sensing, Ottawa, Canada) (Zhao et al., 2009a), and the adjustment coefficient was calculated according to formula (1):

$$L = \frac{(1-\alpha\ )\,L_e\gamma_E}{\Omega_E}, \tag{1}$$

where L_e is the effective *LAI* (acquired by instrumental observation), γ_E is the ratio of the total area of coniferous leaves to the cluster area, the conifer species is 1.4, and α, the ratio of non-leaf factors, such as the trunk, to total leaf area, was 0.12 (Chen, 1996). The adjustment coefficient was calculated as 1.32, which was multiplied by *LAI* measured by the *LAI*−2000*C* canopy analyzer to adjust the canopy *LAI* value according to formula (1).

Data were plotted using R version 4.2.1 software (AT&T Bell Laboratories, New Jersey, USA) and WPS Office 2021(Kingsoft, Beijing, PRC). The relations between *LAI* of *P. crassifolia* and *P*, *AT*, *ST*, and *SWC* were analyzed using SPSS v.21.0 (SPSS Inc., Chicago, IL, USA) with Pearson correlation. Multiple stepwise linear regressions were used to examine the relation of *LAI* with hydrothermal factors. The multiple linear regression model mainly studies the relationship between a dependent variable and multiple independent variables, and its general form can be expressed as formula (2):

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + ... + \beta_\mathrm{k}x_\mathrm{k} + \varepsilon, \tag{2}$$

where *y* is the dependent variable, *x* is the independent variable, β_1, ... β_k are model parameters, and ε is Stochastic error. In this study, *LAI* is used as the dependent variable, and *AT*, *P*, *ST,* and *SWC* are used as independent variables to explore the relationship between them through this model.

3. Results

3.1. Hydrothermal conditions of the study site

Figure 1 shows that the thermal and water of three sample plots in the study site were synchronization. *P* and high temperature were all concentrated in the growing season (May to September). The maximum monthly *P* was 97.4 and 103.3 mm, respectively, in July 2015 and September 2016. The maximum monthly average

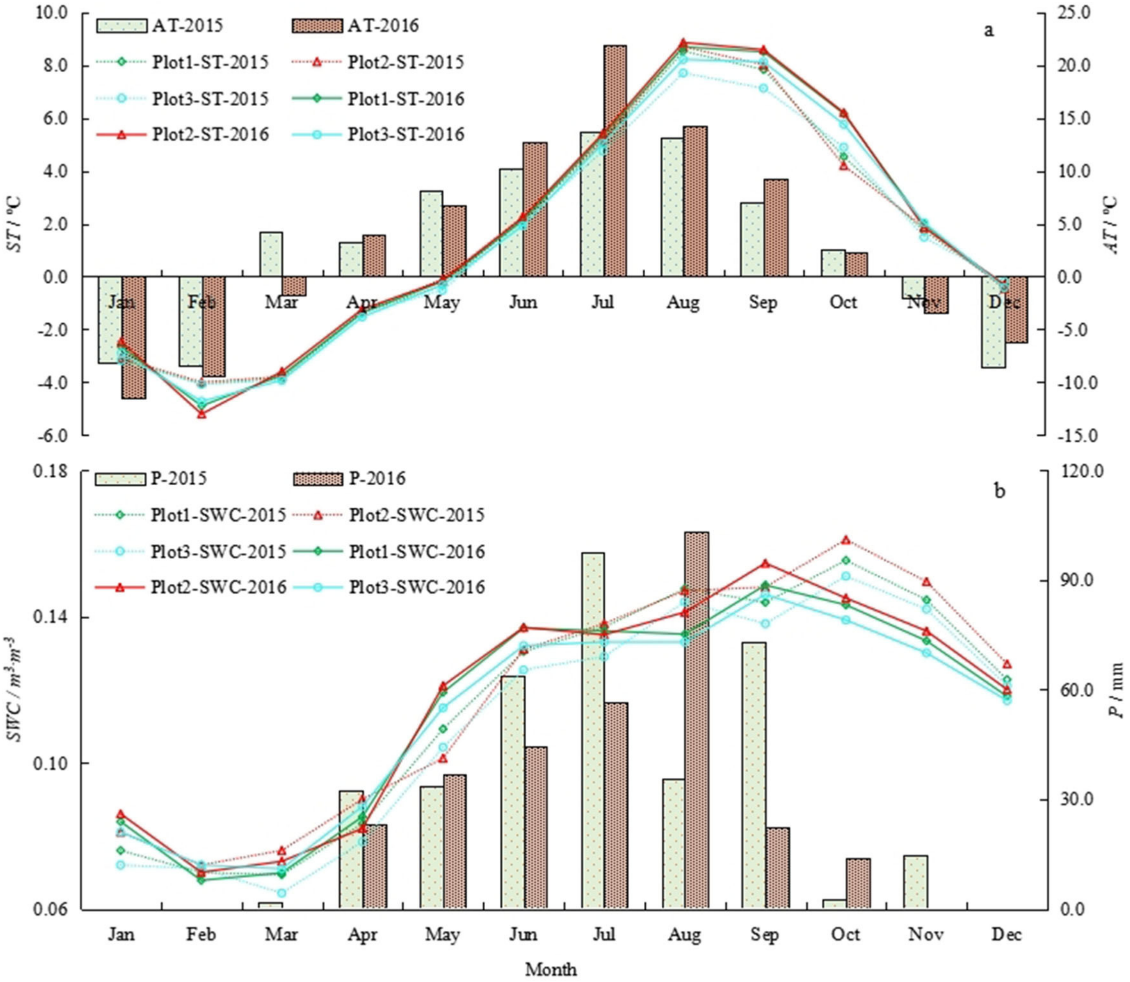

FIGURE 1
(a, b) Monthly average *ST*, *AT*, *P*, and *SWC* of three sample plots in 2015 and 2016.

AT was 13.7 and 21.8°C, respectively, in July 2015 and July 2016. The maximum monthly average *ST* was 8.5 and 8.6°C, respectively, in August 2015 and August 2016. The maximum monthly average *SWC* was 0.16 and 0.15, respectively, in October 2015 and October 2016.

3.2. Seasonal variation of *LAI*

As shown in Figure 2, the *LAI* of *P. crassifolia* in the three sample plots initially increased and then decreased during the two growth seasons (from May to September) in 2015 and 2016. The period from late May to early July was characterized by the rapid growth of *LAI*. Several withered and yellow coniferous leaves fell off in September, even though *P. crassifolia* is an evergreen coniferous forest, and *LAI* started decreasing. According to our field observations, over 2 consecutive years, these fallen leaves were old perennial or diseased withered leaves. In addition, the average, minimum, and maximum *LAI* values of the 1# sample plot were 3.39, 2.57, and 3.99, respectively. The average, minimum, and maximum *LAI* values of the 2# sample plot were 3.51, 2.73, and 4.10, respectively. The average, minimum, and maximum *LAI* values of the 3# sample plot were 3.17, 2.37, and 3.84, respectively. The *LAI* of the 1# and 2# sample plots was similar and higher than the *LAI* of the 3# sample plot. This result is consistent with the surveyed parameters summarized in Table 1.

3.3. Relation between *LAI* and *AT*

Table 2 shows the results of the Pearson correlation analysis between the *LAI* of *P. crassifolia* and *AT*. *LAI* was positively correlated with *AT*, and a significant positive correlation ($p < 0.05$) was observed between *LAI* and *AT* during July–August 2015. *LAI* was positively correlated with *AT* in July and August of 2016 ($p < 0.05$).

3.4. Relation between *LAI* and *ST*

As shown in Figure 3, *P. crassifolia LAI* was positively correlated with *ST* in 2015 and 2016. In 2015, *LAI* was correlated

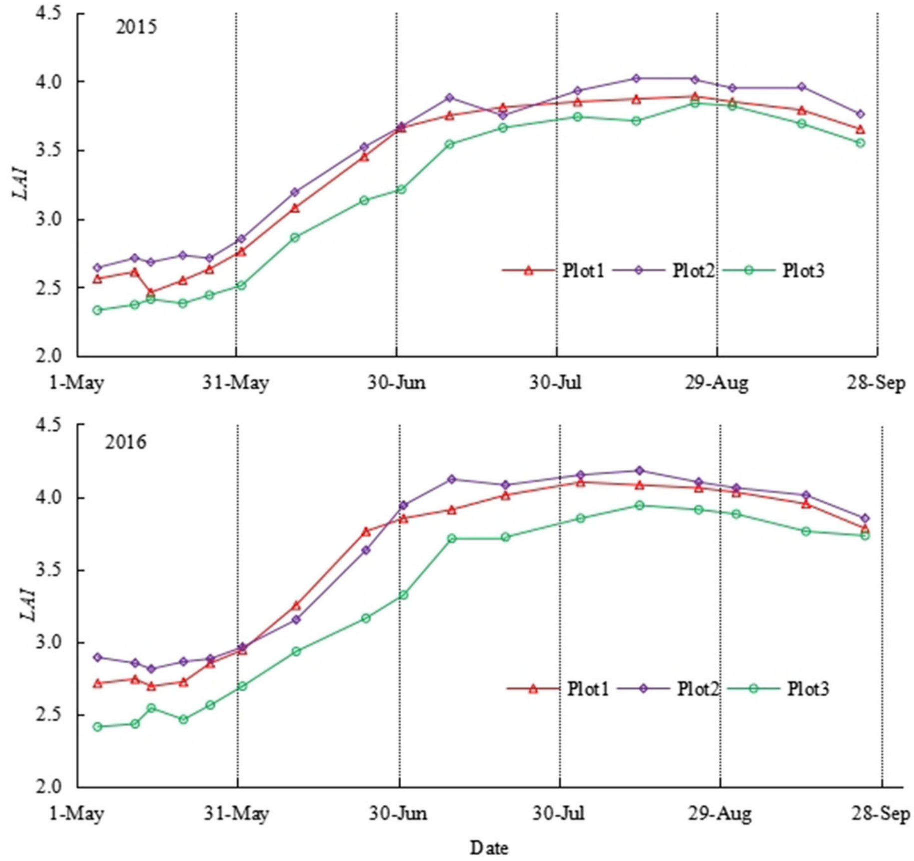

FIGURE 2
Seasonal variation of monthly average *LAI* in different sample plots in 2015 and 2016.

TABLE 1 Investigation of sample sites.

Sample number	Canopy closure	Average forest age (a)	Stand density (strain · ha^{-1})	Average breast diameter (cm)	Average tree height (m)	Average crown (m)
1	0.66	83	1,344	10.4 ± 4.2	7.9 ± 3.9	2.9 ± 0.9
2	0.68	84	1,328	11.9 ± 6.3	8.9 ± 4.0	3.0 ± 0.9
3	0.56	86	1,128	15.5 ± 9.1	10.7 ± 5.6	3.9 ± 1.1

TABLE 2 Pearson's correlation coefficient between *LAI* and *AT* in 2015 and 2016.

Year	Month				
	May	June	July	August	September
2015	0.402	0.334	0.533*	0.878*	0.335
2016	0.434	0.421	0.870*	0.916*	0.418

*$p < 0.05$; **$p < 0.01$.

with ST_{0-40} and ST_{mean} in May, ST_{0-20} and ST_{mean} in June, and ST_{0-80} and ST_{mean} in September ($p > 0.05$). It was positively correlated with ST_{40-80} in May, ST_{20-80} in June, ST_{0-60} and ST_{mean} in July, and ST_{0-60} and ST_{mean} in August ($p < 0.05$). It was significantly positively correlated with ST_{60-80} in July and August ($p < 0.01$). In 2016, *LAI* was correlated with ST_{0-20} and ST_{mean} in May and June, and ST_{0-80} and ST_{mean} in September ($p > 0.05$). It was positively correlated with ST_{20-80} in May and July and ST_{0-80} in July and August ($p < 0.05$). It was significantly positively correlated with ST_{mean} in July and August ($p < 0.01$).

3.5. *Relation* between *LAI* and *P*

The results in Table 3 show that the relation between the *LAI* of *P. crassifolia* and *P* in 2015 was consistent with that of 2016. *P. crassifolia LAI* was correlated ($p > 0.05$) with *P* in May 2015 and 2016. It was positively correlated ($p < 0.05$) with *P* in June, July, and August. It was negatively correlated ($p > 0.05$) with *P* in September. The rainfall distribution showed a large amount of *P* in July and August, during which the values of *LAI* were relatively larger. The maximum *LAI* was 4.02 and 4.18, respectively, which appeared in August 2015 and 2016.

FIGURE 3
Pearson's coefficient of correlation between the monthly average *LAI* and monthly average *ST* across the three plots calculated for each month of the years 2015 and 2016. $^{*}p < 0.05$; $^{**}p < 0.01$.

TABLE 3 Pearson's correlation coefficient between *LAI* and *P* in 2015 and 2016.

Year	Month				
	May	June	July	August	September
2015	0.313	0.461*	0.861*	0.546*	−0.321
2016	0.298	0.553*	0.649*	0.713*	−0.247

$^{*}p < 0.05$; $^{**}p < 0.01$.

3.6. Relation between *LAI* and *SWC*

The results of a Pearson correlation analysis between the *LAI* of *P. crassifolia* and *SWC* in different soil layers are presented in Figure 4. The *LAI* of *P. crassifolia* was correlated with *SWC*, which was different between months. In 2015, it was correlated with SWC_{0-10}, SWC_{20-80}, and SWC_{mean} in May, SWC_{0-80} and SWC_{mean} in June, and SWC_{0-80} and SWC_{mean} in September ($p > 0.05$). It was positively correlated with SWC_{0-80} and SWC_{mean} in July and August ($p < 0.05$). It was negatively correlated with SWC_{10-20} in May ($p > 0.05$). In 2016, the *LAI* of *P. crassifolia* was correlated with SWC_{0-20}, SWC_{40-80}, and SWC_{mean} in May, SWC_{0-80} and SWC_{mean} in June, and SWC_{0-40}, SWC_{60-80}, and SWC_{mean} in September ($p > 0.05$). It was positively correlated with SWC_{0-60} and SWC_{mean} in July and SWC_{0-60} and SWC_{mean} in August ($p < 0.05$). It was significantly positively correlated with SWC_{60-80} in July and August ($p < 0.01$). It was negatively correlated with SWC_{20-40} in May and SWC_{40-60} in September ($p > 0.05$).

3.7. Multiple linear regression analysis between *LAI* and hydrothermal factors

Multiple linear regression analysis was performed between the *LAI* of *P. crassifolia* and *AT*, *P*, *ST*, and *SWC* during different months of the growing season in 2015 and 2016. The results of the multiple linear regression equations are presented in Table 4.

The multiple linear regression model fits the relations between *LAI* and *AT*, *P*, *ST*, and *SWC*. The model passed this test and was statistically significant.

The leaf area index was affected by *AT* and *ST* in May 2015 and 2016. *AT* and *P* mainly affected *LAI* in June 2015 and 2016. *LAI* was affected by *AT*, *ST*, and *SWC* in July 2015 but was affected by *AT* and *ST* in July 2016. *LAI* was affected by *P* and *ST* in August 2015 but was affected by *AT*, *P*, and *SWC* in August 2016. *LAI* was affected by *P*, *ST*, and *SWC* in September 2015 but was affected by *P* and *ST* in September 2016. On a monthly average, *AT* increased by 1°C and *LAI* changed by 2.30. *P* increased by 1 mm, and *LAI* changed by 5.39. *ST* increased by 1°C, and *LAI* changed by 3.18. *SWC* increased by 1, and *LAI* changed by 5.24. Overall, the main hydrothermal factors affecting the canopy *LAI* of *P. crassifolia* differed in July, August, and September.

4. Discussion

Canopy *LAI* often shows highly complex temporal and spatial variations (Zhao et al., 2009b; Liu et al., 2017), even in pure forests of the same age with a single stand structure (Bequet et al., 2012) because of many common environmental factors, such as forest structure, soil factors (moisture and physical and chemical properties), topographical factors (altitude, slope, and aspect) (Bequet et al., 2011; Kinane et al., 2022), and meteorological conditions (Luo et al., 2011; Li et al., 2012). Therefore, attention has been paid to temporal variations in the canopy *LAI* of different vegetation types in different regions.

4.1. Temporal and spatial variation of *LAI*

4.1.1. Temporal variation of *LAI*

Our study showed that *LAI* of *P. crassifolia* exhibited significant seasonal variation. *LAI* reached its maximum value in early August and slightly declined during late September. The large number of new shoots of *P. crassifolia* caused *LAI* to increase in the early growing season, and the fallen leaves led to a slight

FIGURE 4
Pearson's coefficient of correlation between the monthly average *LAI* and monthly average *SWC* across the three plots calculated for each month of the years 2015 and 2016. $*p < 0.05$; $**p < 0.01$.

TABLE 4 Multiple linear regression models of *LAI* with hydrothermal factors in 2015 and 2016.

Years	Month	Stepwise regression equation	N	R^2	F	p
2015	May	$y = 1.362x_1 + 0.287x_3$	15	0.754	13.065	0.084
	June	$y = 3.295x_1 + 14.769x_2$	9	0.923	12.348	0.037
	July	$y = 0.895x_1 + 0.205x_3 + 5.872x_4$	9	0.901	15.792	0.020
	August	$y = 2.125x_2 + 5.365x_3$	9	0.815	10.631	0.135
	September	$y = 1.09x_2 + 0.145x_3 - 0.029x_4$	9	0.982	16.304	0.036
2016	May	$y = 6.954x_1 + 14.253x_3$	15	0.629	20.127	0.041
	June	$y = 3.254x_1 + 7.158x_2$	9	0.775	13.396	0.039
	July	$y = 0.042x_1 + 0.556x_3$	9	0.854	26.671	0.044
	August	$y = 0.327x_1 + 2.836x_2 + 9.879x_4$	9	0.840	15.738	0.019
	September	$y = 4.346x_2 + 1.442x_3$	9	0.967	29.595	0.153

where y, x_1, x_2, x_3, and x_4 represent LAI, AT, P, ST (weighted average of soil temperature) in different soil layers), and SWC (weighted average soil water content in different soil layers), respectively. N represents the number of LAI observations.

decrease in *LAI* throughout the growing season. *LAI* in 2016 was slightly larger than that in 2015, which may be because the newly accumulated branches contributed to certain *LAI* based on our field observations. Our study suggests that the *LAI* of evergreen coniferous forests shows significant seasonal variation.

The annual and interannual variations in pure oak forest *LAI* were studied in the Champenoux forest in France. The results showed that oak *LAI* increased with the growth of new branches at the beginning of the annual growth season; however, the interannual changes were not significant (Bréda and Granier, 1996). The annual and interannual dynamics of vegetation *LAI* were also analyzed using the simple biosphere model (SiB2) method for the Poyang Lake Basin. The results showed that overall *LAI* of different vegetation cover types did not increase or decrease for 20 years but showed an alternating increasing or decreasing trend every 2–3 years, and the variation of evergreen coniferous forest *LAI* was significant (Li et al., 2012), which was consistent with our study. A seasonal dynamic study in the Liupan Mountains of North China showed that larch *LAI* increased linearly with an increase in canopy density, and the change in *LAI* in the growing season presented a single-peak curve (Han et al., 2015).

4.1.2. Spatial variation of *LAI*

As three sample plots were selected at the same altitude and slope, only the seasonal variation in the canopy *LAI* of *P. crassifolia* was studied. However, the spatial distribution of canopy *LAI* of *P. crassifolia* in the Qilian Mountains has been studied. The results showed that the *LAI* of *P. crassifolia* initially increased and then decreased with altitude in the Tianlaochi Basin of Sidalong Forestland in the Qilian Mountains because the limiting factors for the growth of *P. crassifolia* are mainly controlled by water at the low altitude and by the temperature at the high altitude (Zhao et al., 2009b). The spatial variability of canopy *LAI* in dark coniferous forests has also been studied in subalpine western Sichuan. The results indicated that altitude is an important factor affecting *LAI*. The difference in *LAI* between different altitude gradients is extremely significant, and the *LAI* of subalpine dark coniferous forests in western Sichuan increases with altitude (Lǔ et al., 2007). Analysis of the variogram of fir forest *LAI* in the Daxing'an Mountains showed that *LAI* depended on the spatial heterogeneity of months. The spatial heterogeneity of *LAI* in July and November was mainly induced by spatial autocorrelation and accounted for 99.8% and 66.9% of the total spatial heterogeneity, respectively (Liu et al., 2013).

4.2. Effects of hydrothermal conditions on *LAI*

The response of vegetation to hydrothermal conditions is a key process in understanding the terrestrial carbon–water cycle, and attention has been paid to the relationship between vegetation *LAI* and environmental factors (Hebert and Jack, 1998; Meier and Leuschner, 2008; Luo et al., 2011; Shao and Zeng, 2011).

4.2.1. Effects of water on *LAI*

The leaf area index of the different vegetation types was highly correlated with *P* in the preceding 3 months and with an average temperature in the preceding 1 month in the Poyanghu Basin, and both of them were 95% significant. Interannual changes in *LAI* of different vegetation types were highly influenced by interannual changes in *P* in the Poyanghu Basin from May to July (Li et al., 2012). *P* mainly affected the seasonal variation in *LAI*, as was noticed by studying the relation between *LAI* and climatic factors in a *Quercus variabilis* plantation at the southern foot of Taihang Mountain between 2001 and 2019 (Huang et al., 2022). The *LAI* of beech has been found to be mainly controlled by physiological factors related to forest age, while the effects of chemical properties of soil and *P* are relatively low (Bequet et al., 2011). The CMIP5 model was used to study the response of *LAI* to drought, and *LAI* showed irregular increases and decreases with decreasing soil water content (Huang et al., 2016).

Our study implied that the *LAI* of *P. crassifolia* was positively correlated with *P* and highly positively correlated with SWC_{60-80}. This may be related to the root distribution of *P. crassifolia*. *LAI* was negatively correlated with *P* in September, probably because of the decrease in *P* in September in the alpine region.

4.2.2. Effects of temperature on *LAI*

Leaf area index data from remote sensing were used to study the response of global vegetation *LAI* to temperature, which indicated that the season and interannual changes in temperature on a global scale were significantly different in different ecosystems (Zhang et al., 2002). The effect of the slope scale on the *LAI* of *Larix principis-rupprechtii* was studied in the small basin of Liupan Mountain, which showed that the main influencing factors in May were solar radiation and air temperature (Wang et al., 2016; Liu et al., 2017). The monthly maximum temperature was found to be the most influential factor in the dynamics of *LAI* in loblolly pine plantations (Kinane et al., 2022). The correlation between *LAI* and hydrothermal conditions was positive on a time scale and a spatial scale in most regions on the Tibetan Plateau (Wang et al., 2008).

Our study implies that *LAI* is influenced more by temperature and water in July and August in alpine Northwest China. Therefore, an accurate understanding of the temporal and spatial variability of forest canopy *LAI* is highly significant for evaluating forest productivity at multiple scales and for studying the energy and water balance from the basin to the region.

5. Conclusion

The rapidly increasing period of *LAI* of *P. crassifolia* canopy was from late May to early July. The maximum *LAI* of *P. crassifolia* occurred in mid-August. *LAI* of *P. crassifolia* forests also has significant seasonal variation although it is an evergreen coniferous tree species. The main hydrothermal factors affecting the canopy *LAI* of *P. crassifolia* differed in July, August, and September. The *LAI* of *P. crassifolia* was more influenced by temperature and water in July and August. The *LAI*-2200 and TRAC methods are valid for measuring the *LAI* of *P. crassifolia* canopy forests. This study may provide a scientific basis for studying the impact of global change on forest ecosystems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YZ and WZ contributed to the conception and design of the study. WZ wrote sections of the manuscript. YZ and HF organized the database and performed the statistical analysis. YZ wrote and revised the first draft of the manuscript. All authors approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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