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RESEARCH PAPER

Growth in stem diameter of *Larix principis-rupprechtii* and its response to meteorological factors in the south of Liupan Mountain, China

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Abstract: Research related to daily and seasonal pattern of stem growth of *Larix principis-rupprechtii* was carried out with the help of a dendrometer from June to September in 2005 in the Liupan Mountain, Ningxia, Northwestern China. The results indicated that daily fluctuation of stem diameter was rhythmic and it could be divided into three continuous phases: contraction, expansion and stem diameter growth when daily rainfall < 10 mm during the measurement period. Comparatively, it showed a different pattern compared with the former when daily rainfall ⩾10 mm and in the subsequent days. Based on the work done by Deslauriers *et al*. a modified method was designed to calculate daily and cumulative stem growth, and it showed that seasonal pattern of cumulative stem growth was similar among five sample trees. From June and July, stem growth rate was quick and the values were in the range 27.0–44.2 μm per day. Relatively, they took on a slow growth rate from August to September, and the values were under 10 μm per day. And it also showed that there existed a significant difference in stem growth among sample trees, which could be as a result of the difference in tree domain and their positions in the stand. The relationship between daily stem growth and meteorological factors was studied by principle component analysis and partial correlation analysis, and the result indicated that the daily rainfall, daily minimum temperature, daily average solar radiation and vapor pressure deficit were four significant factors which determined the daily stem growth.

Key Words: Dendrometer; *Larix principis-rupprechtii*; stem diameter growth; meteorological factors

Tree growth is determined by several factors such as biological characteristics of the tree species, micrometeorology, site conditions, and forest management practices[1]. As one very important part of the studies on tree growth, stem diameter growth is of great importance in recognizing the mechanism how tree growth is influenced by such environmental factors as meteorology[2]. In China, stem diameter growth of the standing tree in the field is usually measured by a caliper gauge or special manmade mechanical instrument at present[1], which can hardly ensure continuity and integrity of the observation process. At the same time, the data collected by these methods are difficult to be used for analyzing the diurnal and nocturnal change process of stem diameter growth and its environmental response mechanism.

In 1962, Fritts studied the response of tree growth to climatic factors at a short-time scale by means of dendrometer measurement[3]. And dendrometer has been widely accepted to study the stem growth process of the tree species by many researchers overseas since the middle of 1970’s because it could be easily connected to the datalogger to record the growth process of stem diameter at a short-time scale automatically and continually[1,4−7]. It was proved that research into stem growth at hour or even shorter time scales is of great value to understand the response mechanism of tree growth on environmental factors from ecophysiological viewpoint[7]. Unfortunately, there has been no such literature as the method in China up to now.

In the present study, the stem diameter change of *Larix*

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principis-rupprechtii in the south of Liupan Mountain was to be measured by dendrometer, together with micrometeorological factor observation, and the objectives were as follows: (1) to estimate daily stem diameter growth of the tree species, (2) to know seasonal change pattern of stem diameter growth, and (3) to understand the response of stem diameter growth to meteorological factors.

1 Study site

The experiment plot is situated in Xiangshuihe watershed, southern area of Liupan Mountain National Natural Reserve (E106°10'–30', N35°14'–42'), Ningxia, China. The total area of the watershed is 43.74 km^2 and its elevation ranges from 2040m to 2942m. The soil type is of gray-cinnamon at a depth of 30 to 100 cm. The climate of the region is typically temperate and semihumid, and the mean annual temperature varies from 5℃ to 5.8℃. The mean annual precipitation ranges from 600 to 820 mm, of which 87% occurs from May to September. Aridity is below 1.0, and the frostless season is about 100–130d. The mean monthly temperature as well as the monthly temperature and rainfall in 2005 and during 1995–2005 are shown in Fig. 1.

2 Material and method

2.1 Material

The experiment plot was located on a southeast-facing slope with an average angle of 45º, at 2286 m above sea level. The study was carried out in 22-year-old *L. principis-rupprechtii* plantation covering an area of 400 m^2 (20 m×20 m) from June to October in 2005, the stem density was 1275 hm^{-2}, the crown density was 0.6, the leaf area index was 2.3 (Plant Canopy Analyzer, LAI-2000, LI-cor Inc., USA), the tree height was 13.7 m, and the average diameter at breast height (*DBH*) of all trees was 12.2 cm. The understory vegetation was dominated by herb species, e.g., *Carex hancokiana* Maxim., *Artemisia sacrorum* Ledeb. var. *incana* Mattf., *et al.*, and the coverage was about 80%. Shrub species were scarce, mainly including *Rosa hugonis*, and the coverage was about 20%. Five sample trees were selected for dendrometer measurement according to distribution pattern and height of the individual tree; detailed tree measurements were listed in Table 1 and their relative positions were sketched in Fig. 2.

2.2 Method

2.2.1 Principle and measurement of dendrometer

There are two types of dendrometers, point and band, widely used nowadays in the world and both of them work on the same principle. The pressure on the sensor of the dendrometer could transform with the daily fluctuation of the stem diameter including shrinking and swelling, and the pressure difference could change the value of resistance of the sensor. That is, there existed closely correlated relationships between the resistance of the sensor and the instant tension impressed on it; in this way, the change of stem shrinking and swelling could be expressed according to the relationships. At last, the change in the stem diameter of the tree could be monitored automatically and continuously by connecting the sensor to the datalogger.

From June to September in 2005, five healthy sample trees

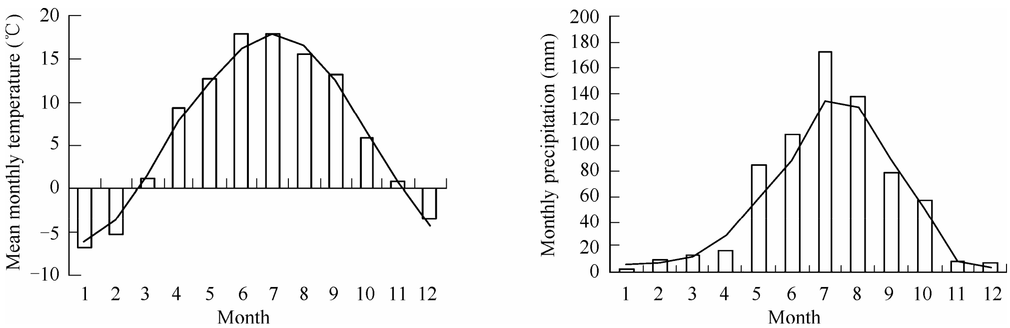

Fig.1 Mean monthly temperature and precipitation at Jingyuan County in 2005 (bars) and 1995–2005 (lines)

Table 1 Characters of 5 sample trees of *L. principis-rupprechtii* for stem diameter change monitored in 2005

Tree number	Sensor number	Tree class[8]	Height (m)	*DBH* (cm)	Canopy (m)		Coordinate	
					Height	Diameter	*X* (m)	*Y*(m)
20	DC 1	Codominant	15.0	15.20	12.8	1.65	10.9	7.5
29	DC 2	Dominant	16.4	14.40	13.8	1.94	14.5	11.6
30	DC 3	Intermediate	12.4	11.00	9.3	1.36	10.8	11.5
31	DC 4	Intermediate	11.8	9.20	9.2	1.35	8.7	11.3
37	DC 5	Dominant	16.2	14.00	13.4	1.85	11.6	14.0

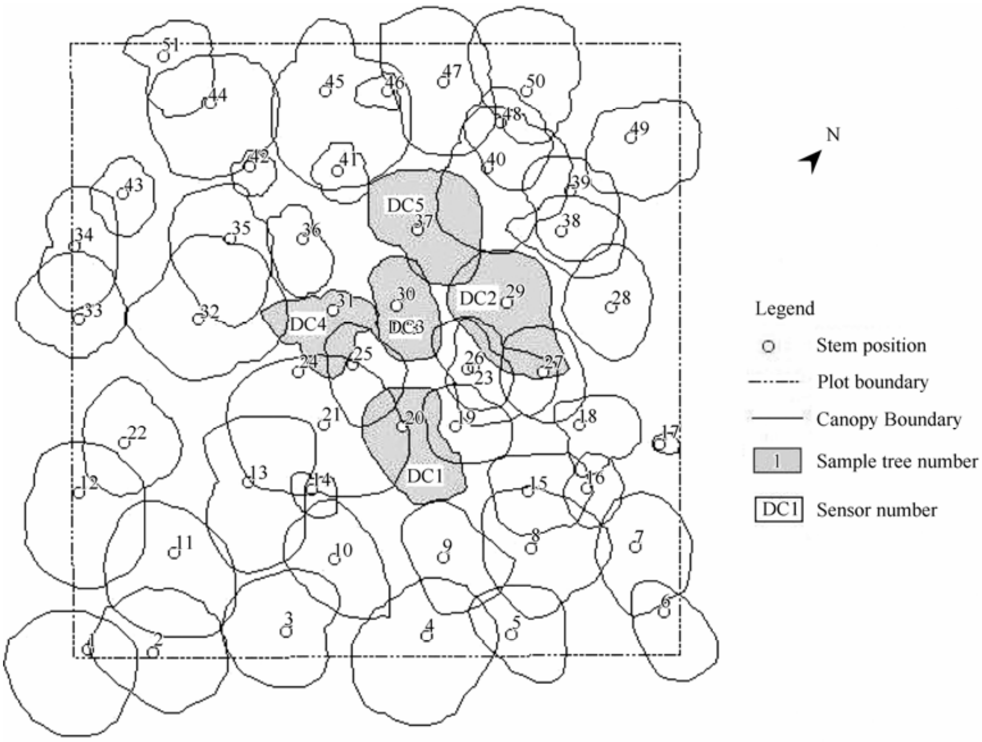

Fig.2 Stem position and canopy projection of 5 sample trees of *L. principi-rupprechtii* in plot for stem diamater variation monitoring

were selected for band dendrometer measurements continuously (DC Type, Ecomatik Inc., Germany, Http: // www. ecomatik.de). And the sensors were mounted at 1.5m above the ground of the sample trees. The process of mounting the sensor was as follows: first, the surface of the stem was smoothened via removing the dried and dead barks by using special tools, passing the wire around the tree trunk and avoiding the tangency between the wire and surface of the stem; second, insert its end through the sensor hole, and fix it with the adjusting screw. Loosen the adjusting screw slightly and pull the wire slowly to achieve an electrical resistance between the yellow and green cables around 2 kohm for installation. Connect the output signal wire to the datalogger (DL2e, Delta Device, Cambridge, U.K.), and the signal wire could be extended up to 100m; finally, send an order for collecting data to the logger by a portable computer, and the time step is 5 min.

2.2.2 Micro-meteorological measurement

A micro-meteorological measurement plot was constructed in an open area, which was 100 m from the dendrometer measurement plot. And it was supposed that the weather condition of the stand canopy was similar to that of the plot[9]. Weather data including solar radiation ($w \cdot m^{-2}$), air temperature (℃), relative humidity (%), wind speed ($km \cdot h^{-1}$) and wind direction (°) were collected by the automatic weather station (Intelimet, Dynamax Co., USA) every 5 min. Vapor pressure deficit (kPa) was calculated by the air temperature and relative humidity.

2.3 Data analysis

The raw data for the dendrometer measurement were downloaded by the portable computer every 7 days, and the data were analyzed with Excel software. The stem position and canopy projection of the sample tree in the stand were scheduled by Acrmap^{TM} (8.3 version) software, and principal components analysis, partial correlation analysis and regression analysis were conducted with SPSS (11.0 version).

3 Results and analysis

3.1 Daily fluctuation and determination of the stem diameter growth

The change in the stem dimension is not only the result of the real xylem formation, but may also be caused by the hydration process of stems, just similar to the shrinking and swelling resulting from the change in water content of the stem itself. So it is impossible to determine the real growth of stem diameter from the raw data of dendrometer measurement. According to the determining method proposed by the Deslauriers *et al*[4], daily change in the stem diameter of *L. principis-rupprechtii* could be divided into three distinct phases: (1) contraction phase, which is defined as the period between the morning maximum and the daily minimum, (2) expansion phase, which is defined as the total period from the daily minimum to the following morning maximum, and (3) stem increment phase, which is defined as part of the expansion phase from the time when the stem radius exceeds the morning maximum until the subsequent maximum (Fig. 3). And the real daily growth of the stem diameter could be calculated on the basis of the definitions of the stem increment phase. However, it doesn't mean that all parts of growth processes only occur in "stem increment phase" defined by Deslauriers *et al*., but the daily growth of the stem diameter is close to the value calculated by the method under relative weather conditions.

Based on the definition, the initiation time of three phases of daily change in the stem diameter of *L. principis-rupprechtii* could be determined in Table 2. The results indicated that the stem diameter began to dwindle to enter in the contraction phase owing to increasing stem sap flow caused by the intensive canopy transpiration from 9:00 to 10:00, and it reached its minimum from 16:30 to 17:30. Then the stem diameter began to swell to enter into the expansion phase as a result of the decreasing canopy transpiration and refilled the water storage caused by the absorption of water by the roots. At last, the stem diameter went through the growth phase of stem diameter and reached its subsequent maximum, and a typical change process of the stem diameter finished in a daily cycle.

The initiation time of three phases of the stem diameter varied largely among sample trees (great standard error) during the whole measurement period in Table 2, which was mainly contributed to the response of stem change on the weather conditions, especially the rain incident. In general, daily fluctuation of the stem diameter presented a periodical cycle as described above under the rainless or little rain conditions (daily rainfall<10mm) in Fig. 4-a. Comparatively, it presented a different pattern from the former under the heavy or continuous rain conditions (daily rainfall⩾10mm); the stem diameter only swelled continuously but not occurred to contract in the daytime in Fig. 4-b. Although the change of the stem diameter presented a periodical cycle during the dry season, the following maximum stem diameter was often lower than the previous one in Fig. 4-c, which meant that the stem did not grow or had a "negative growth" during that period. That is, the method proposed by Deslauriers *et al.* may possibly produce large errors for estimating daily growth of the stem diameter under the weather conditions with continuous rain or drought.

3.2 Estimation of daily growth of the stem diameter

According to the reorganization of daily change in the stem diameter, the modified formula on estimating the daily growth of the stem diameter of *L. principis-rupprechtii* was presented just as follows here, based on the method proposed by Deslauri-

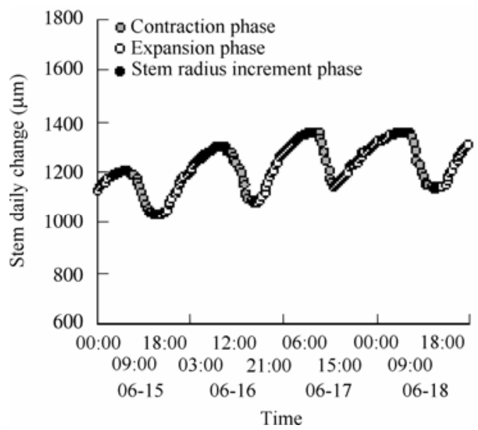

Fig. 3 Daily changes of stem diameter and division of three variation phases of *L. principi-rupprechtii*

Table 2 Initiation time of three phases of daily change of stem diameter of *L. principis-rupprechtii*

DC number	DC1	DC2	DC3	DC4	DC5
Contraction phase	7:14–12:06	7:26–12:28	6:14–12:28	6:54–12:04	6:19–12:05
Expansion phase	12:50–21:52	11:45–21:47	13:32–21:28	12:42–20:46	11:53–21:13
Stem increment phase	0:38–15:48	1:25–15:35	1:32–18:08	3:05–21:47	0:57–16:19

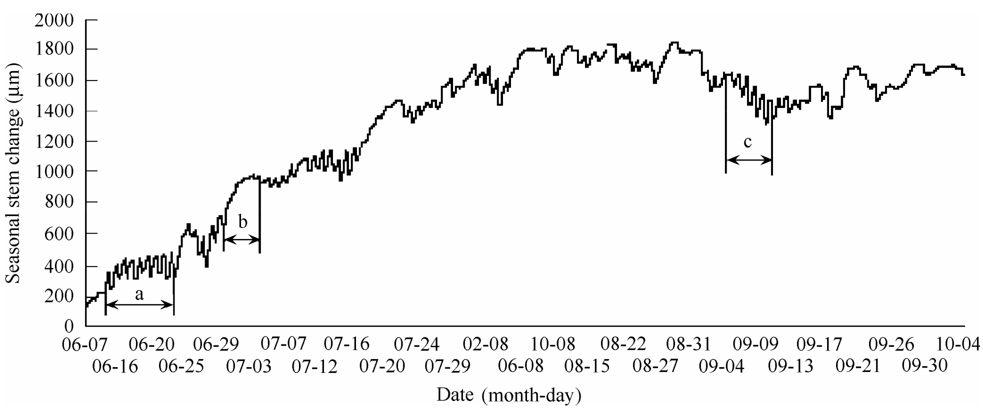

Fig. 4 Seasonal changes of stem diameter of *L. principi-rupprechtii*

ers *et al*.,

$$G_d = \begin{cases} D_{\max\cdot(i+1)} - D_{\max\cdot i} & 0\text{mm} \leqslant P_d < 10\text{mm} \\ \dfrac{1}{n}(D_{\max\cdot af} - D_{\max\cdot bf}) & P_d \geqslant 10\text{mm} \end{cases} \quad (1)$$

In formula (1) , G_d presents daily growth of stem diameter (μm), $D_{\max\cdot i}$ is the maximum of daily stem diameter on the day i , $D_{\max\cdot(i+1)}$ is the maximum of daily stem diameter on the day $i+1$, P_d is daily rainfall (mm); $D_{\max\cdot bf}$ (μm) is the maximum of daily stem diameter on the day just before the period with continual rain; n is the number of days between $D_{\max\cdot bf}$ and $D_{\max\cdot af}$; $D_{\max\cdot af}$ is the maximum of daily stem diameter on a day after the period with continual rain, but $D_{\max\cdot(i+1)} \geqslant D_{\max\cdot i}$ must be the prerequisite. The formula (1) can be explained as follows: under the weather condition without rain or with little rain, the method proposed by Deslauriers *et al*. can be directly applied to calculating daily growth of stem diameter. In the period with average daily rainfall≥10 mm and several days subsequently, supposing that weather in the period has the same effect on tree growth. Its average daily growth can be estimated by the mean of the difference value of daily maximum of the stem diameter from the beginning of continual rainy days to the end of rainy days, which can not only avoid overestimating daily growth of stem diameter during the continual rain days, but also lessen possibilities of negative value of stem growth after the period with continual rain (e.g. the dry season). Therefore, it will reduce the effect of sharp change in atmospheric moisture on daily growth of stem diameter.

3.3 Seasonal pattern of stem diameter growth (see Fig.5)

According to the formula (1) and the method proposed by Deslauriers *et al.*, daily stem diameter growth and the cumulative growth of five sample trees were calculated and the results indicated that seasonal change of daily stem diameter growth showed no significant difference estimated by the two

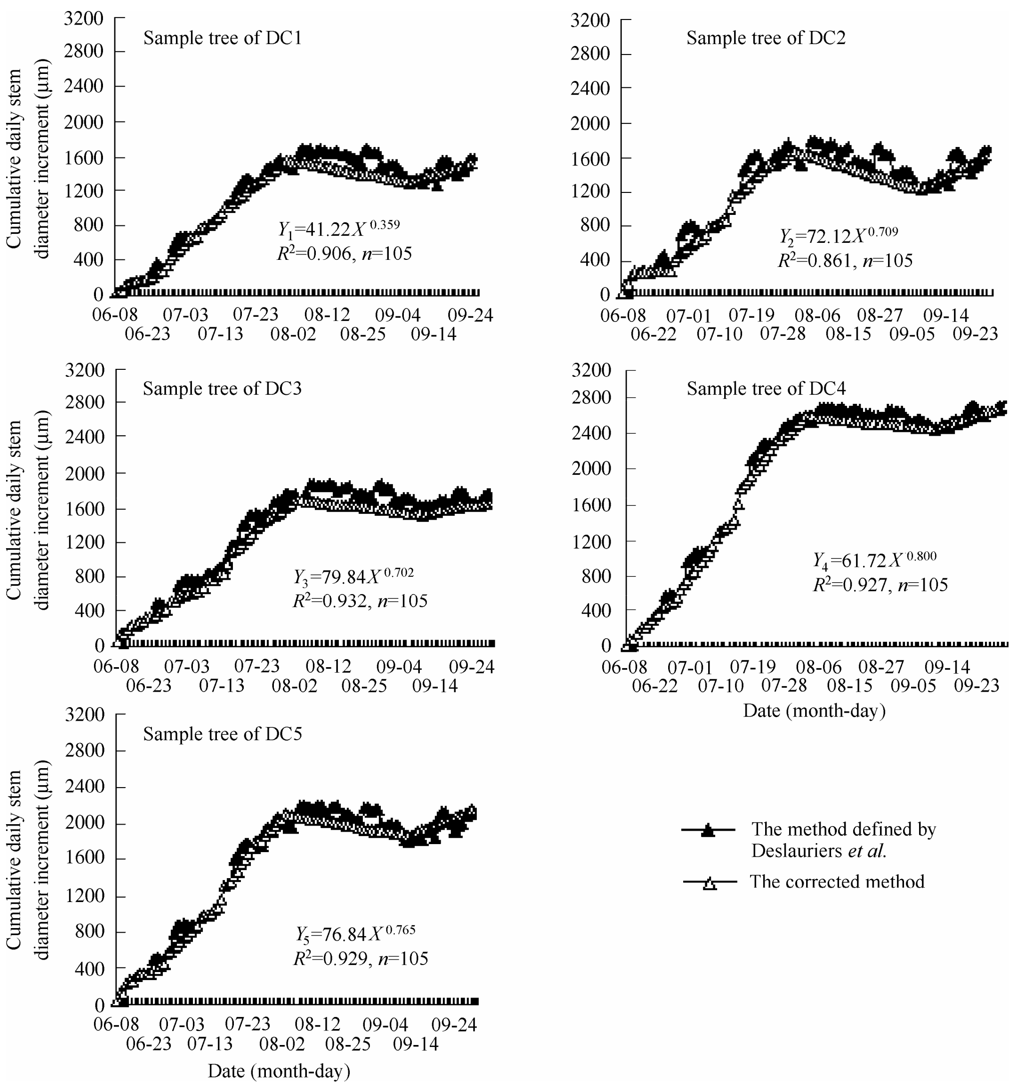

Fig. 5 Seasonal changes of cumulative stem diameter growth of *L. principis-rupprechtii*

Y_1, Y_2, Y_3, Y_4 and Y_5 refer to cumulative stem diameter growth (μm) , respectively, X refers to the day of the year and the first day is Jan. 1

methods, which presented the pattern of quick growth in the first period but slow growth subsequently. The period from June to July was the quick growth period with daily average growth ranging from 27.0 to 44.2μm, and the period from August to September was the slow growth period with daily average growth below 10μm.

Fig. 5 showed that the cumulative curve of stem diameter growth obtained by formula 1 was relatively smooth and narrowed the wave range of calculated values as a result of not considering the effect of period with continual rain on calculating stem diameter growth. What should be mentioned was that the negative value of daily growth still existed after August, and the reason was primarily that in the period without rains from the last ten days of August to the first ten days of September, great contraction in stem diameter occurred because of sharp decrease of water storage, which masked its real growth. In order to quantitatively understand seasonal change of stem diameter growth of *L. principis-rupprechtii*, the curve, which could show cumulative growth process of stem diameter of five sample trees, is fitted, respectively by many function models such as Richard equation, Logistic equation, and allometry equation. The result indicated that seasonal pattern of stem diameter could be well simulated by power function with the determined coefficient all averaging above 0.85; by *F* test, all the equations are significant in Fig. 5.

In Table 3, the monthly means of daily stem diameter growth of five sample trees showed that there existed remarkable individual differences between daily growth and cumulative growth of stem diameter, particularly in the period of quick growth, of which stem diameter of the sample tree of DC4 grew at a faster rate and relative growing rate reached as high as 0.065% in July, which was 2.86 times as DC1. Relatively, DC5, which is ranked second, DC1, DC2 and DC3 grew slowly, showing that the growing rate of stem with small diameter was relatively higher than that with big diameter and this was probably related to biologically inherited traits of *L. principis-rupprechti* or related to the bigger gap in the northwest of which sample DC4 posited (Fig. 2), which is waiting for further analysis. Besides, although daily stem diameter growth of sample DC2 varied greatly (with great standard error), the cumulative growth was not high as a result of balance between positive and negative, which showed that its stem change was much affected by its internal moisture condition.

3.4 Response of stem diameter growth to micrometeorological factors

Daily rainfall (*P*), daily average temperature (T_{mean}), daily minimum temperature (T_{min}), daily maximum temperature (T_{max}), daily average solar radiation (R_{mean}), daily average wind speed (WS_{mean}), daily relative humidity mean (RH_{mean}), and daily average vapor pressure deficit (VPD_{mean}) were originally selected as independent variables affecting stem diameter growth. In order to understand comprehensive information included in the variables, PCA was made on the variables and thus the coefficient matrix among each variable was listed in Table 4, and eigenvalue and contribution were calculated in Table 5.

Table 3 Monthly means of daily stem diameter growth of five sample trees of *L. principis-rupprechtii*

	Jun.	Jul.	Aug.	Sep.
DC1	27.0(0.019%)±18.2	33.3(0.023%)±16.6	− 4.2(− 0.002%)±9.9	6.0(0.004%)±8.4
DC2	28.6(0.020%)±40.4	36.4(0.025%)±38.7	− 9.3(− 0.006%)±10.8	9.3(0.008%)±15.2
DC3	32.8(0.030%)±23.0	34.2(0.031%)±29.6	− 1.8(0.002%)±10.7	3.6(0.003%)±5.5
DC4	44.2(0.050%)±22.5	56.9(0.065%)±35.6	− 0.9(0.001%)±11.7	7.9(0.009%)±7.7
DC5	35.8(0.027%)±30.0	45. 3(0.034%)±28.5	− 3.2(0.002%)±12.7	8.6(0.006%)±9.8

Note：The values in the bracket are relatively stem growth rate

Table 4 Correlation coefficient matrix among micro-meteorological factors

Correlation coefficient	T_{mean}	P	R_{mean}	WS_{mean}	RH_{mean}	T_{max}	T_{min}	VPD_{mean}
T_{mean}	1.000	0.144**	0.280**	0.427**	0.067	0.841**	0.895**	0.287**
P		1.000	− 0.443**	0.026	0.424**	− 0.125*	0.338**	− 0.369**
R_{mean}			1.000	0.159*	− 0.718**	0.647**	− 0.081*	0.779**
WS_{mean}				1.000	− 0.020	0.307**	0.386**	0.199*
RH_{mean}					1.000	− 0.313**	0.379**	− 0.391**
T_{max}						1.000	0.585**	0.591**
T_{min}							1.000	− 0.041
VPD_{mean}								1.000

Note：The values marked ** and * mean that they are significant at P=0.01 and P=0.05, respectively

It is shown in Fig. 5 that the cumulative contribution rate of the first and second components reached as high as 76.618%, and information loss rate was 23.382%, which could basically reflect the information including the micrometeorological factors. Simultaneously, principle component equation could be obtained on the basis of the eigenvector of the first and second components as follows:

$$Y_1 = 0.879VPD_{mean} + 0.667T_{max} + 0.851R_{mean} - 0.683RH_{mean} + 0.295T_{min} + 0.427T_{mean} - 0.363P + 0.389WS_{mean} \quad (2)$$

$$Y_2 = -0.343VPD_{mean} + 0.369T_{max} - 0.324R_{mean} + 0.640RH_{mean} + 0.918T_{min} + 0.750T_{mean} + 0.560P + 0.405WS_{mean}$$

In the equation of the first component Y_1, the coefficient of VPD_{mean} and R_{mean} is higher, then T_{max} which is the daily maximum temperature is also higher, whereas the coefficient of RH_{mean} and P is negative, which shows that Y_1 is the comprehensive meteorological factor reflecting the potential evapotranspiration in the region. In the equation of the second component Y_2, the coefficient of T_{min} and T_{mean} is higher, followed by that of P and RH_{mean}, whereas the coefficient of VPD_{mean} and R_{mean} are negative, which shows that Y_2 is the comprehensive factor reflecting water and temperature condition in the region and it directly affects stem diameter growth.

Taking the first and second components as horizontal coordinate and vertical coordinate, respectively, the two-dimensional classified map of the eight micrometeorological factors is drawn as shown in Fig. 6. The results showed that the eight micrometeorological factors could be further divided into three categories: ① The correlation coefficient of P and RH_{mean} was 0.424, which was closely related to water required by cell division and to that of extension of stem cambium layer and, therefore, was considered as one of the major factors influencing stem diameter growth (see Table 5). ② The correlation coefficient of T_{mean}, T_{max}, T_{min} and WS_{mean} was significant and closely related to accumulation and consumption of photosynthate of the tree, which was, therefore, the major factors directly affecting stem diameter growth (see Table 4). ③ The correlation coefficient of VPD_{mean} and R_{mean} is 0.779 and closely related to such physiological process as photosynthesis which is regulated by the stomatal aperture, which was thus accepted as the indirect factor affecting stem diameter growth.

In order to further quantify the responsive relation of stem diameter growth to meteorological factors, partial correlation analysis was used to analyze further relationship as shown in Table 6 and the result indicated that the four factors, namely, P, T_{min}, R_{mean} and VPD_{mean}, showed significant correlation with

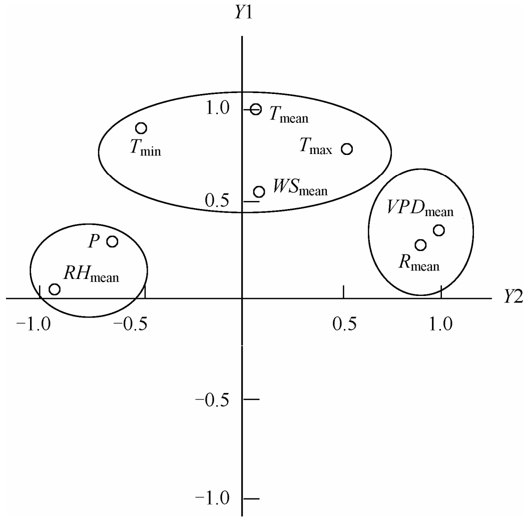

Fig. 6 Coordinate of the first and the second components and classification of micro-climate factors

Table 5 Eigenvalue and contribution in PCA

Component	1	2	3	4	5	6	7	8
Eigenvalue	3.478	2.651	0.780	0.681	0.282	0.080	0.028	0.021
Contribution (%)	43.475	33.143	9.753	8.510	3.521	0.996	0.346	0.256
Cumulative contribution (%)	43.475	76.618	86.370	94.881	98.402	99.398	99.744	100

Table 6 Partial coefficients between daily stem growth of *L. principis-rupprechtii* and meteorological factors

Number	T_{mean}	T_{max}	T_{min}	P	R_{mean}	WS_{mean}	RH_{mean}	VPD_{mean}	Sample number
DC1	0.252	0.034	0.418**	0.496**	– 0.315**	– 0.126	0.360**	– 0.255**	125
DC2	0.229	-0.012	0.420**	0.480**	– 0.322**	– 0.080	0.369**	– 0.272*	125
DC3	0.271*	0.073	0.416**	0.477**	– 0.224*	– 0.090	– 0.304*	– 0.198*	125
DC4	0.394**	0.209	0.477**	0.495**	– 0.093	0.012	0.226*	– 0.079**	125
DC5	0.269	0.056	0.428**	0.501**	– 0.267*	– 0.119	0.339**	– 0.232*	124
DC1–5	0.272	0.063	0.423**	0.480**	– 0.247**	– 0.079	0.319**	– 0.210**	619

The values marked ** and * mean that they are significant at P=0.01 and P=0.05, respectively; The values in the line of DC1–5 are gained by using data from all of five sample trees daily stem diameter growth, whereas factors T_{max} and WS_{mean} did not. The factors T_{mean} and R_{mean} showed different correlation with daily stem growth among sample trees, which might be primarily related to microenvironmental difference of the stand where sample trees posited. For instance, stem growth of sample DC4 showed no significant correlation with R_{mean}, which was because the height of the tree was relatively small in the stand and absorbs less solar radiation; its growth is mainly related to temperature change caused by indirect radiation. Sample trees DC1, DC2 and DC5 belong to the dominant and sub-dominant stem of the stand. When its crown is directly exposed to solar radiation, stem diameter growth will show significant correlation with solar radiation.

When PCA and the partial correlation analysis are together taken into consideration, the four factors, namely, P, T_{min}, R_{mean} and VPD_{mean} are finally selected as the major micrometeorological factors affecting stem diameter growth and the related linear model was established by polylinear regression analysis as follows:

$$Y = -7.131 + 5.242P - 0.085R + 10.848T - 60.807VPD$$

$$R = 0.558 \quad n = 619$$

Where Y is stem diameter growth (μm), P is daily rainfall (mm), R is average daily radiation ($W \cdot m^{-2}$), T is average daily temperature, and VPD is vapor pressure deficit (kPa), and the regression equation is significant on the basis of F test.

4 Discussion

4.1 The definition and estimation of daily growth of the stem diameter

The variation of stem diameter is a conjunct result of stem volume variation caused by xylem formation with the change in internal moisture content of the stem, of which the former is an irreversible process caused by cell division and extension of cambium layer[10], and the latter is a reversible process as a result of physical expansion and contraction of stem volume caused by its internal moisture balance[11,12]. Based on the method defined by Deslauriers *et al*.[5] for calculating daily stem diameter growth of *L. principis-rupprechtii*, daily stem diameter growth could be estimated more precisely owing to preferable separation of real stem growth from the dendrometer measurement during noncontinuously rainy days. However, negative values would frequently occur when subject to this method under the weather conditions involving heavy rain and under the subsequent days, which often occur in semiarid and semihumid regions. Generally, researchers consider "negative-value growth" of stem diameter as zero[5] or as lost data[6] in the process of the data analysis because it is difficult to give reasonable explanation from biological point of view.

The modified formula was presented in the study based on the method defined by Deslauriers *et al*., and the problem of "negative-value growth" could be solved to estimate real stem growth preferably under the transition weather condition period from the dry season to the rainy season (from June to July), during which the growth of stem diameter was rapid. However, under the transition period of weather condition from rainy to dry seasons (from August to September) during the slow growth period of stem diameter, negative value still existed sometimes, which is because the real growth value of stem diameter is masked by its decreasing volume caused by water loss from the stem under the continual drought weather condition. According to the report made by Mäkinen *et al*.[1], stem diameter change is much more affected by moisture condition of tree itself, such as contraction and expansion of the stem, and the raw data of dendrometer measurement can not directly show real growth process of xylem under extreme weather conditions (e.g. continuous drought and rainy days). Hence, further research is needed with regard to this problem, such as on how to distinguish effects of impact factors and how to precisely obtain real growth data of stem diameter from theoretical dendrometer measurement.

In addition, as reported by Mäkinen *et al*., the seasonal pattern of stem growth of *Picea abies* (L.) Karst. showed an "S" type curve during the entire growth season, namely, change in stem growth rate followed the order of lowly-quickly-lowly[1]. Comparatively, the seasonal pattern of stem growth of *L. principis-rupprechtii* presented a power function curve during the whole measurement period in our study, namely, the change in stem diameter rate experienced a quick growth in the former period and a slow growth in the latter one, which resulted from lack of data related to the stem in early growth season (i.e. April to May) necessary to reflect the whole seasonal pattern of the stem growth, owing to relatively late beginning of measurement period (i.e. June) in our study. But the fluctuation of stem growth of *L. principis-rupprechtii* was similar to a former study from June to September.

4.2 The response of the daily growth of stem diameter to meteorological factors

PCA and partial correlation analysis indicated that rainfall was one of the major meteorological factors affecting daily stem diameter growth, which is coincident with majority of research done previously[2,4,5]. In our study, it was revealed that the effects of water on tree growth was simultaneously manifested in relative humidity and vapor pressure, with the former showing positive correlation, whereas with the latter showing negative correlation, which was not a result of the stem surface (bark) absorbing air moisture and subsequent expansion in humidity, but because of increased water content in the stem which is as a result of weakened canopy transpiration, and root's continual water absorption under the weather condition of high relative humidity or low vapor pressure deficit. Herzog pointed out[4] that, when we do not consider real xylem formation, daily stem diameter change was closely associated with sap flow, and that it was often caused by change in stem moisture content, and not by direct absorption of water from air by the outer surface (bark).

It was reported[13,14] that temperature, particularly night temperature, was the primary factor which affected cell extension and the expansion of stem cambium layer. The research showed that daily lowest temperature is the only temperature factor which showed significant correlation with growth of stem diameter in all of the sample trees. This was because the daily lowest temperature often occurred in night or dawn, which is the active time for stem diameter growth. Thus, it could be seen that the results drawn from the present study were coincident with former studies.

In brief, the four micrometeorological factors filtered by PCA and correlation analysis showed significant correlation with daily stem diameter growth, but there existed a remarkable individual difference in the response of stem diameter growth to some meteorological factors, e.g., solar radiation. Therefore, to have an understanding of response mechanism of stem diameter growth to meteorological factors, further research is necessary related to the stem diameter change affected by such factors as the internal moisture dynamic balance in stem, individual difference among trees, and its related microenvironmental differences in the stand.

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References

[1] Mäkinen H, Nöjd P, Saranpää P. Seasonal changes in stem radius and production of new tracheids in Norway spruce. Tree Physiology, 2003, 23: 959–968.

[2] Chen Z H, Zhang D M, Guo Z H. Diameter growth of three tree species in the lower subtropical climate. Acta Ecologica Sinica, 1999, 19(6): 939–943.

[3] Fritts H C. The relevance of dendrographic studies to tree ring research. Tree Ring Bull, 1962, 24: 9–11.

[4] Herzog K M, Häsler T R. Diurnal changes in the radius of a subalpine Norway spruce stem: their relation to the sap flow and their use to estimate transpiration.Trees,1995, 10: 94–101.

[5] Deslauriers A, Morin H, Urbinati C, *et al*. Daily weather response of balsam fir (*Abies balsamea* (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Qubec (Canada). Trees, 2003, 17: 477–484.

[6] Downes G, Beadle C, Worledge D. Daily stem growth patterns in irrigated *Eucalyptus globules* and *E. nitensin* relation to climate. Trees, 1999, 14: 102–111.

[7] Mclaughlin S B, Wullschleger S, Nosal M. Diurnal and seasonal changes in stem increment and water use by yellow poplar trees in response to environmental stress. Tree Physiology, 2003, 23: 1125–1136.

[8] Kimmins J P. Forest Ecology. New York: Macmillan, 1987. 340–341.

[9] Wang Z F, Zhu T Y, Zhu J W, *et al*. Forest Meteorology. Beijing, China: China Forestry Publishing House, 1985.

[10] Wang S S, Gao R F, Wu G M. Plant Physiology. Beijing, China: China Forestry Publishing House, 1991.

[11] Irvine J, Grace J. Continuous measurements of water tensions in the xylem of trees based on the elastic properties of wood. Planta, 1997, 202: 455–461.

[12] Offenthaler I, Hietz P, Richter H. Wood diameter indicates diurnal and long-term patterns of xylem water potential in Norway spruce. Trees, 2001, 15: 215–221.

[13] Richardson S D, Dinwoodie J M. Studies on the physiology of xylem development. I. The effects of night temperature on tracheid size and wood density in conifers. J. Inst. Wood Sci., 1960, 6: 3–13.

[14] Antonova G F, Stasova V V. Effects of environmental factors on wood formation in Scots pine stems. Trees, 1993, 7: 214–219.