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Stem Radius Variation in Response to Hydro-Thermal Factors in Larch

Yuan Tian, Qiuliang Zhang *, Xuan Liu and Meng Meng

Department of Forest Management, Inner Mongolia Agricultural University, Hohhot 010019, China; sacr1986@emails.imau.edu.cn (Y.T.); 984706126@emails.imau.edu.cn (X.L.); mm2022916@emails.imau.edu.cn (M.M.)

* Correspondence: zqlemail@imau.edu.cn; Tel.: +86-186-8602-8468

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Abstract: The response mechanism of the tree stem radius variation to hydro-thermal factors is complex and diverse. The changes of TWD (tree water deficit-induced stem shrinkage) and GRO (growth-induced irreversible stem expansion) are respectively driven by different factors, so that their responses to hydro-thermal factors are different. The stem radius variation and its matching hydro-thermal factors experimental data was measured and determined at 0.5 h time scale in larch (*Larix gmelini* Rupr.) forest of the Daxing'anling region of the most northeastern part of China. Response characteristics of the stem radius variation to hydro-thermal factors have been found by analyzing the data under different time windows. The stem radius variation mainly responded to the changes in precipitation and relative humidity. The main driving factors for TWD were sap flow density and solar radiation. The response of GRO to hydro-thermal factors was complex, varied a lot under different time scales. During the analysis of the response of tree radial growth, changes of the stem radius can be divided to TWD and GRO to implement separate studies on their responses to hydro-thermal factors. In this way, it becomes easier to discover the response of TWD under drought stress and the responding mechanism of GRO to hydro-thermal factors.

Keywords: radial growth; stem shrinkage; water deficit; environmental factors; sap flow; plant-climate interactions

1. Introduction

Under natural growing conditions, the stem, height and shape of the tree change from time to time. In addition, this change is the growth of the tree. The stem radial growth is an important indicator for measuring the growth and development level of individual trees. It is the basis for studying the structure of trees and their species. The variations of stem radius not only determine the changes of tree height, sectional area, volume, but are also the basis for guiding the forest management, tending, and thinning, and determining forest stand productivity [1]. In addition, due to the height of the tree and other reasons, the stem radius variation of the tree is an indicator that can be easier acquired and determined compared with the tree height or shape.

The study of stem radius variation in time scale could not be conducted at high precision due to the technical restrictions in the past. As for the comparatively traditional method, such as the annual ring method, can only obtain corresponding data on a larger time scale, or use a diameter tape or self-made mechanical instrument to regularly measure the diameter at breast height (stem diameter at 1.3 m height of the tree), which can hardly guarantee the accuracy, continuity and integrity of the observed data, not to mention the study on the short-term growth rules and its response to the environmental factors. The appearance of tree stem radius recorder has made it possible to study tree stem radius variation of high-resolution [1,2]. The study of tree radius variation based on high-resolution helps to understand the physiological radial growth characteristics of trees on a smaller time scale and to improve the understanding of xylem function, so as to better understand the function of trees [3].

Water is an important component of tree protoplasm while the air temperature is a necessary condition for tree radial growth and development. The radial growth of trees is closely related to the water and air temperature. At the time when evaluating the dynamic response of trees to environmental hydro-thermal factors, the high-resolution radius change is considered to have huge potentials to unveil the stem radius variation system responding to the environment by analyzing and simultaneously observing the environmental factors [3,4]. The long-term study on tree stem radius variation time series provides phenotypic data on growth, phenology, and survival to reveal plant growth characteristics, mechanisms behind plant growth, tree CO_2 emissions, and tree adaptation potential for climate [5,6]. Scholars have carried out a large number of studies on different environments, different climates, and different tree species by taking stem radius changes of trees at different time scales as the measure of study. Stem radius variational indicators used in the research mainly included maximum daily shrinkage, stem radius increment, and daily stem radius variation. However, there researches are all direct analysis based on the tree stem radius or diameter change, which could not distinguish the tree water deficit-induced stem shrinkage (TWD) and growth-induced irreversible stem expansion (GRO) of the trees, and blocked the quantification of growth in a short period of time [7]. Zweifel [8] divided the stem radius variation into TWD and GRO and proved that the zero-growth assumption (no radial growth during periods of stem shrinkage) is more accurate than the linear growth assumption (linear growth during periods of stem shrinkage). However, up to now, this study hasn't been deeply conducted, which resulted in the lack of theoretical support for the study on responding of tree stem radius growth change mode to the environmental factors and the consequences resulted by being stressed by a certain factor [8]. Although the stem radius variation is mainly due to the dynamic transport of water between tissues, many different plant physiological mechanisms and physical characteristics can affect the curve trend characteristics of the stem radius change. In addition, the response mechanism of the tree stem radius variation is complex and diverse. The changes of TWD and GRO are respectively driven by different factors, so that their responses to hydro-thermal factors are different.

Larch (*Larix gmelini* Rupr.) is the main tree species in the Daxing'anling forest area. The special environmental hydro-thermal conditions in the Daxing'anling forest area maintain the normal growth and development of the larch forest. In this study, the response of the tree stem radius dynamic changes of the middle and high latitude frozen soil of the virgin forest region under high-resolution to the hydro-thermal factors was investigated based on the measurement and determination of the synchronous changes of stem radius, TWD, GRO, and precipitation, sap flow density, relative humidity, vapor pressure deficit, solar radiation, and air temperature at the 0.5 h time scale of larch in the year of 2017. The specific objectives of this study were: to reveal the response characteristics of tree stem radius variation and the TWD and GRO which were divided based on the zero-growth assumption (no radial growth during periods of stem shrinkage) to the hydro-thermal factors of precipitation, sap flow density, relative humidity, vapor pressure deficit, solar radiation and air temperature at different time windows (0.5 h, 1 day, 7 days and 21 days), thus finding the information that hasn't been sufficiently used under high-resolution scale.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Inner Mongolia Daxing'anling Forest Ecosystem Research Station (50°54′24″ N, 121°30′5″ E) in northeastern part of China (Figure 1), with an elevation of 791 m. This area belongs to the cold temperate humid climate zone. During the last five years (2013–2017), the basic climate data in this region was as follows: annual average temperature: −3.8 °C; maximum temperature: 32 °C; minimum temperature: −45.2 °C; annual average sunlight time:

2594 h; total annual activity temperature: 1403 °C; annual freezing period: over 210 days; and annual precipitation: 483 mm, mainly concentrated in July–September. The forest coverage rate in this area was 75%, of which, the larch is the dominant species, accompanied with species of white birch (*Betula platyphylla* Suk.). The vegetation began to grow in mid-April, rapidly grew in July and August, and then began to wither and fall into the end of growth in mid-September. This area is one of the main development areas of permafrost in China. The seasonal frozen soil and perennial permafrost are distributed in this area. The larch forest and frozen soil maintain the cold and wet environment conditions of cold temperate coniferous forest.

The specific study site is located in the original larch forest northeast to Inner Mongolia Daxing'anling Forest Ecosystem Research Station of Forest. According to the forest form, forest age, tree distribution and growth status, a 25 m × 25 m long-term experimental plot (50°56′24″ N, 121°30′35″ E) was established to conduct the basic information investigation. The plot has an elevation of 853.78 m, an east-west slope of 1°, and a north-south slope of 4°. The trees on this plot are all larch, totally amounting for 86 trees, of which 24 are dead wood. After excluding the dead standing trees, the average crown width of the trees in the plot was calculated to be 3.93 m, the average diameter at breast height (stem diameter at 1.3 m height of the tree) was 19.6 cm, the average tree height was 16.66 m, and the clear bole height was 8.95 m. The canopy density of the plot was 0.8. The sample trees in the larch plot were healthy tree with good growth status, no damage. The stem was round and smooth, and the diameter at breast height and height of the sample trees were close to the average diameter at breast height and height of the trees in the plot.

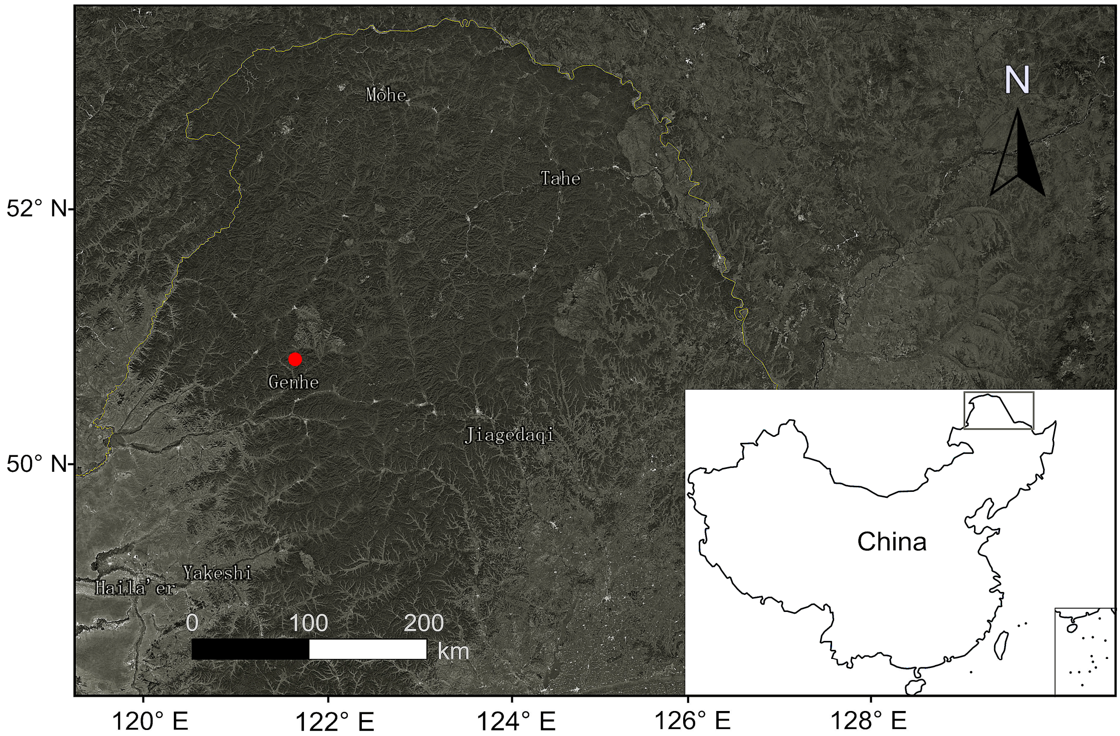

Figure 1. Location of the study area (the red point).

2.2. Measurement of Larch Stem Radius Variation

The experiment devices were installed on 6 selected sample trees of larch. Automatic band dendrometers were used for measuring stem radius variations of larch at 1.3 m, with the accuracy of ±7 μm. The measured data was recorded by the data collector in frequency of recording once per every 0.5 h. The remaining battery power was checked regularly to guarantee to replace the lithium battery in low power. The instruments were regularly maintained to ensure that no branch, fruit or snow fall and stay on the sensors for long periods of time. According to the growth of the trees, the sensors were periodically re-installed to ensure proper tension of the sensing wires, thus improving the measurement accuracy.

2.3. Measurement of Related Hydro-Thermal Factors

Meteorological data acquisition sensors were installed on an automatic weather station to collect the data of hydro-thermal factors. The hydro-thermal factors include precipitation (TE525 device, Campbell Scientific, Logan, UT, USA), air temperature (HMP45C device, VAISALA, Helsinki, Finland), relative humidity (HMP45C device, VAISALA, Helsinki, Finland), and solar radiation (CM11 device, Campbell Scientific, Logan, UT, USA). The data acquired for every 0.5 h is recorded by a unified data collector (type CR3000, Campbell Scientific, Logan, UT, USA). Vapour pressure deficit was calculated from air temperature and relative humidity.

Thethermal dissipation method [9] was applied to determine the stem sap flow density of larch. Sensors (SF-G, Campbell Scientific, Logan, UT, USA) were installed at 1.5 m of stem of the selected sample tree, facing north. In addition, sensors were covered with aluminum foam film to prevent the sensors from being affected by rain and solar radiation. The data collector (type CR1000, Campbell Scientific, Logan, UT, USA) recorded the data once every 10 min.

2.4. Data Analysis

TWD and GRO were calculated [8] from stem radius variations:

$$\mathrm{TWD(t)} = \left\{ \begin{array}{ll} \max[\mathrm{SR}(<\mathrm{t})] - \mathrm{SR(t)}, & \mathrm{SR(t)} < \max[\mathrm{SR}(<\mathrm{t})] \\ 0, & \mathrm{SR(t)} \geq \max[\mathrm{SR}(<\mathrm{t})] \end{array} \right\}, \tag{1}$$

$$\mathrm{GRO(t)} = \left\{ \begin{array}{ll} \mathrm{SR(t)} - \max[\mathrm{SR}(<\mathrm{t})], & \mathrm{SR(t)} \geq \max[\mathrm{SR}(<\mathrm{t})] \\ 0, & \mathrm{SR(t)} < \max[\mathrm{SR}(<\mathrm{t})] \end{array} \right\}, \tag{2}$$

where t refers to the current record; <t refers to historical records; SR is stem radius; TWD is tree water deficit-induced stem shrinkage; GRO is growth-induced irreversible stem expansion.

Statistical analysis of data was performed by using SPSS 13.0 (SPSS Inc., Chicago, IL, USA). To analyze the relationship between the distribution status of larch stem radius variation and hydro-thermal factors and the digital characteristics, the period of the cambium activation was divided into drought and moist stages. In addition, the stem radius variation, TWD, GRO and sap flow density, relative humidity, vapour pressure deficit, precipitation, solar radiation, and air temperature were adopted to conduct descriptive statistics and analysis. After that, the Pearson correlation analysis and significance test of these variables on the time scale of 0.5 h and the time window of 1 day, 7 days and 21 days were carried out, and the correlation between stem radius variation and different hydro-thermal factors was found. Origin 7.5 (OriginLab Corporation, Northampton, MA, USA) was adopted for drawing, and the standard deviation of data was adopted for drawing the error bars.

3. Results

3.1. Environmental Conditions for Growth of Larch

The environmental conditions of the study area were consistent with the climatic conditions of the study site. In 2017, the annual average temperature in the study area was −4.3 °C, and the frost-free period was 90 days. The overall temperature in 2017 was lower than the annual average temperature in 2012–2016. The activation period of the cambium includes the entire frost-free period. With an average temperature of 10.4 °C, this period has higher temperature than any other periods throughout the year.

In 2017, the average relative humidity was 67%, the annual precipitation was 336 mm, and the longest continuous no precipitation days were 45 days. The year was relatively dry with no more than the average prescription of period of 2012–2016. The average relative humidity in the larch growing season in 2017 was 69.3%, and the total precipitation was 299.7 mm (Figure 2). According to the precipitation, the growth season of larch could be divided into two stages: drought season (11 April to 17 June, total precipitation 52.9 mm) and moist season (18 June to 1 October, total precipitation 246.8 mm).

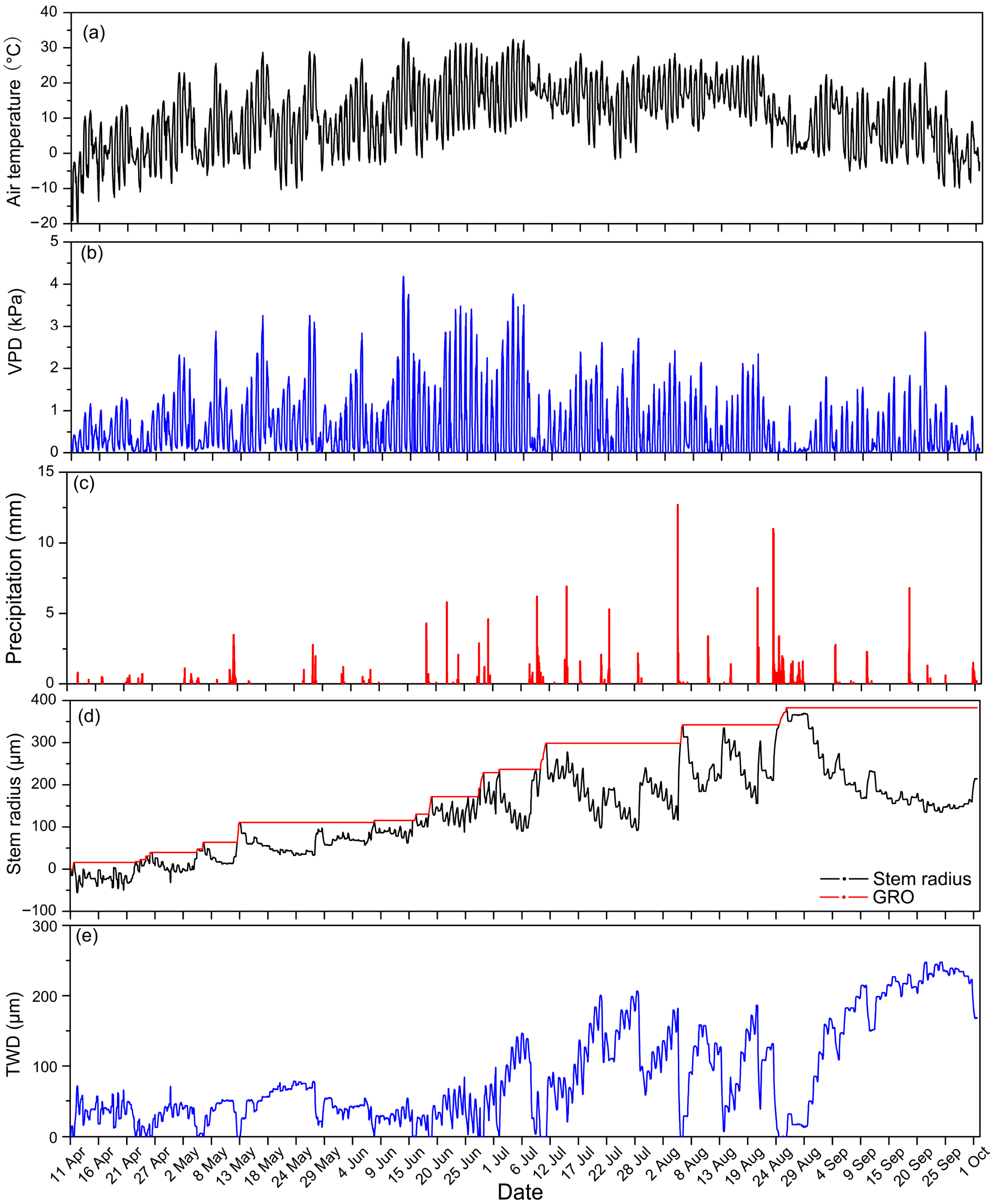

Figure 2. (**a**) Seasonal course of mean halfhour air temperature, (**b**) halfhour mean of vapour pressure deficit (VPD) and (**c**) daily totals of precipitation. (**d**) Seasonal changes of halfhour mean of stem radius partitioned into tree water deficit-induced stem shrinkage (TWD), and (**e**) growth-induced irreversible stem expansion (GRO) in 2017.

3.2. Change Trends of Larch Stem Radius Variation and Hydro-Thermal Factors

There were differences in stem radius variations and TWD changes of larch from 11 April to 1 October (Figure 2). In the overall trend of change, the seasonal variation of stem radius had a certain consistency with the seasonal variation of rainfall. The trends of TWD, air temperature and vapour pressure deficit on the image were roughly the same. Comparison for mean value and standard difference of stem radius variations and TWD in the drought and moist stages were conducted respectively (Table 1). In the drought period, the stem radius variation and TWD both had the characteristics of small value and small change range. In the moist season, the values of the two were large and varied greatly. However, the average changes of the TWD in moist season were lower than stem radius variations. In addition, the increment of GRO was the main component of stem radius variations of trees. The difference of variation coefficients between stem radius variation/TWD and the air temperature is the minimum. In addition, ranges of their respective changes are the closest (Table 2).

Table 1. The means and standard deviations of stem radius and tree water deficit-induced stem shrinkage in two stages: drought season (11 April to 17 June) and moist season (18 June to 1 October).

	Stem Radius			Tree Water Deficit-Induced Stem Shrinkage		
	Drought Season	Moist Season	Relative Growth Rate	Drought Season	Moist Season	Relative Growth Rate
Mean	37.798	198.141	524.21%	37.737	117.554	311.51%
Standard deviation	40.538	66.036	162.90%	19.107	72.633	380.14%
n	3264	5089	-	3264	5089	-

The relative growth rate means changes of statistical indicators in drought season phase relative to those in the moist season phase.

Table 2. The mean, standard deviations and variation coefficients of stem radius variations and hydro-thermal factors during the period of the cambium activation (11 April to 1 October).

	Mean	Standard Deviation	Variation Coefficient	*n*
Stem radius	135.486	97.060	71.64%	8353
TWD	86.365	69.814	80.84%	8353
GRO	215.497	116.141	53.89%	299
SFD	0.016	0.059	361.74%	4465
Relative humidity	69.653	27.422	39.37%	8353
VPD	0.543	0.698	128.53%	8353
Precipitation	0.072	0.484	674.61%	4177
Solar radiation	203.664	252.549	124.00%	8353
Air temperature	10.389	9.263	89.16%	8353

TWD: tree water deficit-induced stem shrinkage; GRO: growth-induced irreversible stem expansion; SFD: sap flow density; VPD: vapour pressure deficit.

From 11 April to 1 October, the GRO of the larch showed a stepwise rising trend (Figure 2), which was in line with the zero-growth assumption (no radial growth during periods of stem shrinkage). Each time period of GRO change was made of statistics and each time period of change generating was counted. The trends of seasonal changes of GRO, air temperature and relative humidity were the same (Figure 3). After dividing the drought season and moist season, GRO increased by 130.422 μm in the drought season and 252.279 μm in the moist season. The changes mainly concentrated in the moist season. The difference of variation coefficients of GRO and the air relative humidity was the minimum, and the changes of the two are comparatively flat and gentle (Table 2).

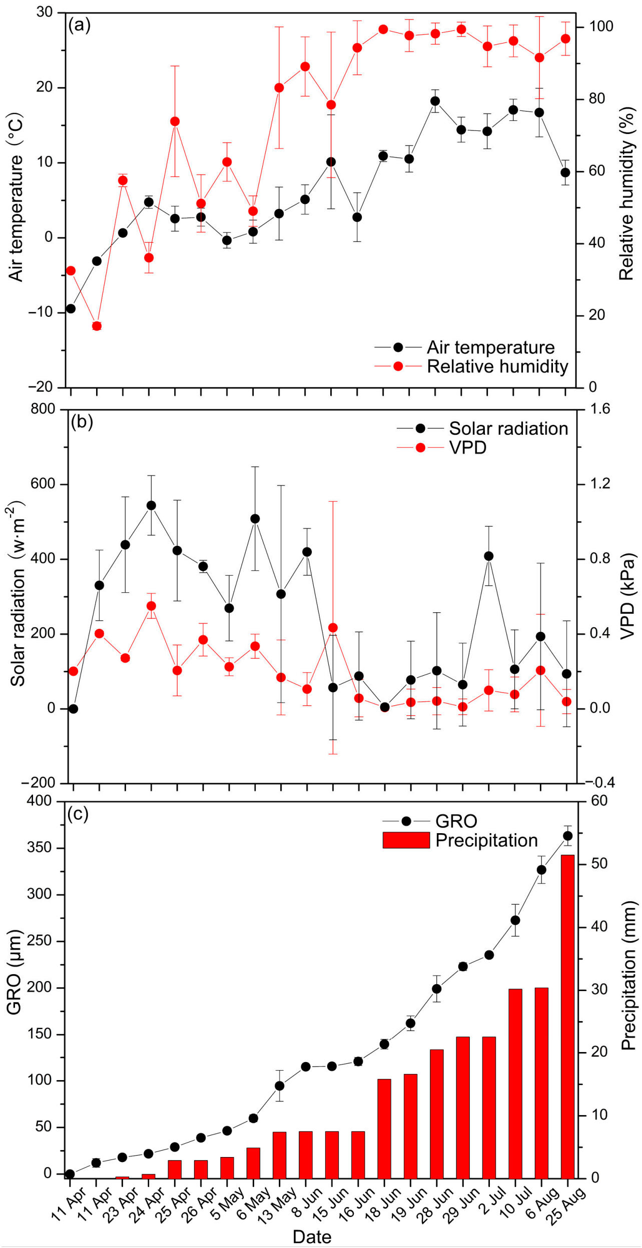

Figure 3. (**a**) Changes of mean air temperature, mean relative humidity, (**b**) mean solar radiation, mean vapour pressure deficit (VPD), (**c**) cumulative precipitation and growth-induced irreversible stem expansion (GRO) in each time period. Each time period of GRO change was made of statistics and each time period of change generating was counted.

3.3. Larch Stem Radius Variations and Its Response to Hydro-Thermal Factors

It was found from the correlation analysis (Table 3) between variations of larch stem radius and the hydro-thermal factors (precipitation, sap flow density, relative humidity, vapor pressure deficit, solar radiation, and air temperature) from 11 April to 1 October that the stem radius variation had high responsiveness to precipitation and air relative humidity in different time windows. In addition, the correlations between the stem radius variation and the precipitation, and between the stem radius variation and air relative humidity were both positive. As the time window became longer, some certain hysteresis of the response was eliminated, and the correlation between stem radius variations and hydro-thermal factor basically reached the maximum at the time window levels of 7 days and 21 days. At the same time, however, the level of significance verification of the correlation between stem radius variations and hydro-thermal factors had also declined. In the time window of 21 days, the correlation between stem radius variations and vapour pressure deficit, solar radiation and air temperature changed from significant to insignificant. The correlation between stem radius variations and sap flow density gradually increased as the time window enlarged. In the 21 days time window, the stem radius variation change mainly responded to changes in the moisture factor.

Table 3. Comparison of Pearson correlation coefficients between stem radius variations and hydro-thermal factors in different time scale.

	Precipitation	SFD	Relative Humidity	VPD	Solar Radiation	Air Temperature	$SFD_{clear\ days}$
$SR_{0.5\ h}$	**0.068 *****	**−0.040 ****	**0.478 *****	**−0.189 *****	**−0.079 *****	**0.282 *****	−0.041
$SR_{1\ day}$	**0.235 ****	−0.102	**0.805 *****	**−0.367 *****	**−0.362 *****	**0.39 *****	-
$SR_{7\ day}$	**0.556 ****	**0.588 ****	**0.939 *****	**−0.443 ***	**−0.481 ***	**0.493 ***	-
$SR_{21\ day}$	**0.818 ***	**0.801 ***	**0.982 *****	−0.44	−0.582	0.635	-
$TWD_{0.5\ h}$	0.01	**0.093 *****	**0.094 *****	−0.016	**−0.095 *****	0.005	**0.209 *****
$TWD_{1\ day}$	−0.025	**0.209 ***	**0.194 ***	−0.107	**−0.262 *****	−0.021	-
$TWD_{7\ days}$	−0.056	**0.647 *****	0.384	**−0.427 ***	**−0.573 ****	−0.067	-
$TWD_{21\ days}$	0.146	**0.839 ****	0.591	−0.559	**−0.723 ***	0.103	-
GRO_{period}	**0.366 *****	**0.351 *****	**0.602 *****	**−0.327 *****	**−0.341 *****	**0.568 *****	0.046
$GRO_{1\ day}$	**0.158 ***	0.159	**0.688 *****	**−0.323 *****	**−0.4 *****	**0.273 *****	-
$GRO_{7\ days}$	0.357	**0.716 *****	**0.833 *****	**−0.51 ****	**−0.606 ****	0.309	-
$GRO_{21\ days}$	0.631	**0.917 ****	**0.937 ****	−0.546	**−0.715 ***	0.222	-

SR: stem radius; TWD: tree water deficit-induced stem shrinkage; GRO: growth-induced irreversible stem expansion; SFD: sap flow density; VPD: vapour pressure deficit. Each time period of GRO change was made of statistics and each time period of change generating was counted. Significant correlations are in bold. Significance levels: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

TWD had a high correlation with some hydro-thermal factors under the time window of 7 days and 21 days. In the 7 days time window, the correlations with sap flow density and solar radiation were high and both reached extremely significant levels. In the 21 days time window, the main driving factors for TWD were sap flow density and solar radiation. TWD had no significant correlation with air temperature at any time window scale. The correlation between TWD and sap flow density in clear days was extremely significant on a half hour scale.

The correlation between the change of GRO period (make statistics on each time period of GRO changes, counting for time periods for each appearing change) and the hydro-thermal factor were extremely significant ($p \leq 0.001$), and the correlation with each factor was high, in which, the correlation with relative humidity and air temperature were the best, both above 0.5. Correlation analysis of the change of radius and sap flow density of larch in clear days (Table 3) showed that TWD had a high correlation with the sap flow density of sunny days and reached an extremely significant level ($p \leq 0.001$). GRO had a high correlation with sap flow density, relative humidity and solar radiation in the time windows of 7 days and 21 days. According to the larger time window analysis, GRO mainly responded to changes in moisture and sunlight.

4. Discussion

In the drought period, stem radius variations, TWD, and GRO have small values and small changes, while in the moist season, the values and changes are large. Changes in stem radius, TWD, and GRO are mainly concentrated in the moist season. Many previous studies [10–13] have proved that precipitation plays an important role in the increase of tree stem radius. The stem radius variation of the tree is positively correlated with precipitation. Under the condition of sufficient environmental moisture, the tree stem radius increases rapidly, while in the case of water shortage, the growth is slow or the radius shrinkage may occur. Deslauriers et al. [14] applied a simple causal model and found that the stem radius variation indirectly responds to changes in precipitation. The reason for the stem radius shrinkage is the transpiration during the daytime, and the reason for the enlargement is that the roots absorb water from the soil to supplement the using amount during the daytime. The main function of precipitation is to increase the moisture in the stem and help maintain a high water potential that requires by cell swelling [15]. After the cambium is reactivated, the expansion and shrinking of the stem radius consists of a hydration cycle caused by dehydration [14] and replenishment caused by the consumption of stored water in the stem [16]. In addition, precipitation has a direct impact on the expansion of the stem radius [17]. Precipitation can reduce the loss of water from the stem caused by water stress during transpiration and maintain the expansion of the stem.

In the 21-day time window, the stem radius variation mainly responded to the change of water factor, and the correlation with vapour pressure deficit, solar radiation and air temperature was not significant. The change in stem radius depended on physiological activity [18] and the correlation with air temperature was not significant [19–21]. The relationship between stem radius variations and total daily sunlight radiation was not tight [19]. Solar radiation and vapour pressure deficit were the key meteorological factors affecting tomato stem radius variation [20]. In different species, the response characteristics to solar radiation and vapour pressure deficit may be inconsistent due to different experimental environmental conditions and species characteristics. The negative correlation between stem radius variations and air temperature was caused by the effect of air temperature on the duration of the phase and does not have a direct physiological effect on tree growth mediated by metabolic activity on a daily scale [14]. In addition, King et al. [22] reported that the tree stem shrinkage was caused by low air temperature frost during the growth of trees. When the temperature drops below -5 °C, the plant will lower the temperature, indicating that the tree can avoid freezing of the xylem stem above this air temperature. The phenology of the cambium was also air temperature driven, which was considered to be the main reason for the variation of stem radius [23]. In cold climates, the effect of air temperature on the stem radius variation is expected to increase relative to hydrological factors [24]. In the case of frost, with the sharp decrease in air temperature, the larch also showed a significant shrinkage of the stem radius in September. However, from the middle of April to the end of September, it showed no tendency of effect increase of air temperature on stem radius variation relative to hydrological factors. The vegetation process of the cambium only carries out under proper temperature, and this vegetation process can only be reactivated when the average temperature reaches a certain threshold [25].

Stem radius variations mainly responded to the changes in precipitation and relative humidity. The stem radius variation was positively correlated with rainfall and relative humidity [26]. It needs to consider the effect of relative humidity on the stem radius variation [27]. The stem radius variation was positively correlated with daily average relative humidity and negatively correlated with the average vapour pressure deficit [19]. Since the relative humidity has great explanatory power, the deep analysis on the stem radius variation's response to atmospheric moisture conditions was intensively focused on relative humidity rather than vapour pressure deficit.

The main driving factors for TWD were sap flow density and solar radiation. As for the TWD response to changes in sap flow density [28], due to the transpiration and unbalance of root water absorption [29], as well as the process of changing osmotic, there was reversible stem radius changes caused by moisture reduction of trees. Only the sap flow density and the vapour pressure deficit directly affected the duration of the contraction phase. For all species, these results [14,30] are consistent with the results of the positive effects of sap flow and transpiration coupling on the duration of the increase in the radius of the stem. In fine weather, the stored water contributed about 10% to daily transpiration, and in rainy days, this data rose to 65%. At the moment with the maximum transpiration, the contribution of internally stored water to transpiration could reach 75% [21]. The photosynthesis of the woody tissues maybe also a key factor in resisting drought stress [31,32] by maintaining plant carbon and water functions. The negative impact of solar radiation on stem radius variation was considered to be related to TWD, not solely due to GRO [33]. TWD has no significant correlation with air temperature at any time window scale. The growth of the plant itself is the best indicator of its water status [8,34]. TWD can be used as a biological indicator of the moisture status of trees, which reflects the effect of water loss on the tree stem radius change. The maximum daily shrinkage calculated based on stem radius variations, as an indicator of radius change, has good sensitivity in diagnosing plant water content [20]. However, maximum daily shrinkage does not split irreversible growth and reversible stem shrinkage caused by water change in stem radius variations. Through this study, it was found that TWD has sensitivity, the stem radius variation accuracy is poor compared with TWD, and TWD has great potential as a moisture change indicator.

The response of GRO to hydro-thermal factors was complex, and varied a lot under different time scales. GRO had a correlation with the studied hydro-thermal factors at the hourly scale, and had the best correlation with relative humidity and air temperature. The time windows of 7 days and 21 days had a high correlation with the sap flow density, relative humidity and solar radiation. Analyzing under the larger time window, GRO mainly responded to changes in moisture and sunlight. The GRO of the growing cells increased radially due to the division in cambium and expansion of wood and bark cells [29]. The growth is related to precipitation [35]. In addition, the solar radiation has an effect on the irreversible stem growth [33].

At different time windows, the stem radius variation of larch showed different characteristics in response to hydro-thermal factors. The correlation between the stem radius variation or its divided TWD, GRO, and hydro-thermal factors reached the maximum degree at the time windows of 7 days and 21 days. The change in stem radius significantly responded to changes in the moisture factor in the Soil-Plant-Atmosphere Continuum. However, this type of response has certain hysteresis [36]. As the time window grows longer, the hysteresis was eliminated to certain extent. Matten et al. [33] found the time-correlation curve of the energy-related forest meteorological variables of solar radiation and vapour pressure deficit were positively correlated with the average air temperature, and moisture factor appeared as restrictive factor. Under the longer time windows of 7 days and 21 days, the daily stem radius variation was mainly generated due to the changes in stem volume caused by changes of moisture factors. When considering the time window of 7 days and 21 days, the stem radius variation's response to environmental factors will be changed, resulting in reliable data on irreversible stem growth. When the window is 7 days, the growth rates of different species were highly synchronized. When the observation window was extended from 1 day to 7 days and 21 days, Köcher et al. [19] found that the stem radius variation of most species had a high correlation with the relative humidity. During these longer integration periods, the increase in radius due to expansion will decrease with the increase of GRO. At 7 days and 21 days long time scales, when the radial growth of stems was related to environmental factors, the correlation of relative humidity and rainfall to radius change were significantly affected and enhanced; while the correlation of air temperature, vapour pressure deficit and solar radiation to stem radius variation was reduced.

5. Conclusions

We analyzed the stem radius variation of larch and its divided TWD and GRO responses to the hydro-thermal factors of precipitation, sap flow density, relative humidity, vapour pressure deficit, solar radiation, and air temperature under the condition of 0.5 h time resolution, and three other time windows of 1 day, 7 days and 21 days. We conclude that the stem radius variation mainly responded to the changes in precipitation and relative humidity. The main driving factors for TWD were sap flow density and solar radiation. The response of GRO to hydro-thermal factors was complex, varied a lot under different time scales. This study preliminarily showed that the division of TWD and GRO would help to facilitate the response research of tree growth due to climate changes under high-resolution conditions. During the analysis of the response of tree diameter growth, radius changes of the stem can be divided to TWD and GRO to implement separate studies on their responses to hydro-thermal factors. In this way, it becomes easier to discover the response of TWD under drought stress and the responding mechanism of GRO to hydro-thermal factors.

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