

Study on the variation characteristics and influencing factors of stem water content of *Acer truncatum* during the overwintering period

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Research Article

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Abstract

Stem water content is a pivotal parameter that characterizes the vitality of plants and maintains their internal water balance. Given the insufficient comprehension regarding the stem water content characteristics and its influencing factors during different stages of the overwintering period, the study, focusing on *Acer truncatum*., developed an Internet of Things (IoT)-based ecological information monitoring system. The system incorporated a proprietary stem water content sensor, allowing non-invasive, in-situ and real time acquisition of stem water content while monitoring diverse environmental parameters. We conducted a detailed elucidation of stem water content variation characteristics and its responses to diverse environmental factors. The results showed: (1) During the overwintering period, stem water content exhibited diurnal variations characterized by " daytime ascent and nighttime descent" across the three stages, exhibiting differences in the moment when the stem water content reaching extremal values and daily fluctuations ranges. Stem water content exhibited minimal fluctuations during deciduous and bud-breaking stages but experienced significant freezing-thawing alternations during the dormant stage, leading to increased daily fluctuation range. (2) Pearson correlation coefficients between environmental parameters and stem water content varied dynamically across stages. Path analysis revealed: during the deciduous stage, stem temperature and saturation vapor pressure deficit were dominant factors influencing stem water content; during dormant stage, air temperature and saturation vapor pressure deficit directly impacted stem water content; during the bud-breaking stage, the primary parameters affecting stem water content were saturation vapor pressure deficit and stem temperature. The study provides valuable insights into unveiling the water transport patterns within tree stems tissue and their environmental adaptation mechanisms during the overwintering period, aiding in the scientific development of winter management strategies to protect trees from severe cold and freezing damage, while fostering healthy growth in the subsequent year.

1. Introduction

For the majority of plant species inhabiting temperate and subarctic regions, the predominant environmental stressor during the winter dormancy period is exposure to low temperature (Larran et al., 2023; Allsup et al., 2023). In many cases, this exposure can induce freezing-thawing cycles of water within various plant tissues such as stem tissue (McCulloh et al., 2023). Specifically, when the ambient temperature drops to a certain threshold, the transition of liquid water within plant tissues to solid ice occurs; Conversely, when the ambient temperature rises to a certain threshold, the solid ice within plant tissues undergoes a transition back to liquid water (Maruta et al., 2022). The potential consequences of stem water freezing expansion, notably in terms of causing xylem vessel rupture and subsequent reduction or loss in xylem hydraulic conductivity (Charra-Vaskou et al., 2023). In severe cases, this phenomenon can trigger freezing-thawing embolism, thereby affecting water transport within the xylem (Taneda et al., 2022). Moreover, the occurrence of multiple freezing-thawing cycles during the winter dormancy period may cause irreversible damage to plant physiology, metabolism, and productivity (Loka et al., 2019), significantly impacting water supply capacity in subsequent growing seasons. Consequently, exploring variation characteristics of stem water content and its influencing factors during the overwintering period holds crucial significance.

Currently, certain studies dedicated to elucidating the dynamics of stem or branch internal water content, as well as freezing-thawing phenomena under low-temperature stress, necessitate the application of slicing analysis in controlled laboratory settings for accurate assessments, despite the associated irreversible damage inflicted on plants (Liu et al., 2021). To achieve non-destructive analysis, some scholars have recently turned to advanced imaging technologies such as nuclear magnetic resonance imaging (Wang et al., 2022; Ishikawa et al., 2016), thermal infrared imaging (Ding et al., 2022), or spectroscopy (Repo et al., 1994), successfully capturing shifts in internal plant water content or freezing-thawing phenomena. However, the high cost of these instruments poses substantial limitations, particularly for prolonged field studies. To overcome these challenges, some researchers have explored plant stem water content changes or freezing-thawing phenomena from the perspective of in-situ and real-time monitoring. For instance, the application of stem diameter micro-variation sensors for scrutinizing changes in stem diameter enables the indirect characterization of internal water content and its freezing-thawing alternations within the stem tissue (Gutmann et al., 2017). Nevertheless, this approach fails to precisely capture authentic changes in stem water content, and the measurement values are susceptible to the influence of various environmental parameters (Dobbert et al., 2021). Several studies have employed sensors based on the principles of time domain reflectometry (TDR), frequency domain reflectometry (FDR), and the standing wave ratio to investigate stem water content changes and its freezing-thawing phenomena in plants. Sparks et al. (2001) quantified the water content and ice content of pine stems using TDR sensors during the winter. Similarly,

Wang et al. (2017) employed TDR sensors to observe the interconversion of liquid water and solid ice in larch and poplar stems under fluctuating ambient temperatures. However, the high cost of TDR sensors and their potential for causing irreversible damage to tree stems pose notable challenges (Li et al., 2023). Sun et al. (2019) detected internal water content changes and freezing-thawing phenomena within apple tree stem tissue during the winter by employing FDR sensors, and proposed a freezing-thawing model. Concurrently, Hao et al. (2013) detected freezing incidents in Chinese fir tree stem during the winter employing FDR sensors. Zhao et al. (2021) conducted a detailed exploration of freezing-thawing characteristics and ice content within the stem tissue using an LWFTD sensor based on the standing wave ratio principle. Additionally, Tian et al. (2023) employed a BVIC sensor to monitor real-time variations in ice content and freezing-thawing rates of tree stems.

In summary, current research has primarily focused on elucidating the phenomena of plant stem water freezing-thawing alternations and ice content variations during the dormant stage of the overwintering period. However, there is a noticeable gap in the literature concerning the detailed variation characteristics of stem water content throughout different stages of the entire overwintering period. Furthermore, the impact and magnitude of various environmental factors on stem water content remain inadequately explored. For this reason, the study selected the common ornamental tree species *Acer truncatum* in northern China as the research subject, and developed an Internet of Things (IoT)-based ecological information monitoring system. The system incorporates a living tree stem water content sensor based on standing wave ratio principle with independent intellectual property rights, providing in-situ, non-destructive and real-time acquisition of stem water content, and simultaneously obtains various environmental parameters. The study endeavored to comprehensively investigate: 1) the variation characteristics of stem water content during different stages of the overwintering period; 2) the impact and magnitude of various environmental parameters on stem water content at different stages of the overwintering period. The study contributes to the early identification and assessment of potential frost damage risks and adaptability for trees throughout the entire overwintering period. Moreover, it carries profound implications for researchers and forestry managers, providing guidance on rational responses to meteorological variations and the implementation of scientifically informed strategies for winter protection and management of trees.

2. Materials and methods

2.1 Research Area and Material

The study was conducted at the nursery of Beijing Forestry University, located in Ba Jia San Qing Yuan, Haidian District, Beijing (116.33° E, 40.00° N), with an elevation of approximately 50 m. The predominant soil type in the nursery is clay loam with a pH ranging between 7 and 8. The climate in this region is characterized by a temperate humid monsoon climate, featuring low rainfall in spring and autumn, abundant rainfall in summer, and cold arid winters. The annual average evapotranspiration is approximately 1800 mm.

In March 2022, twelve well-established *Acer truncatum* plants with straight trunks, no visible scars, and an average diameter at breast height of 5.25 cm were carefully selected and transplanted into pots with a diameter of 85 cm and a height of 46 cm. Throughout the study period, irrigation was administered based on feedback from soil moisture sensors within the pots to maintain optimal moisture conditions for each plant.

2.2 Stem water content sensor

Figure 1 presents the schematic and physical representation of the autonomously developed stem water content sensor based on the standing wave ratio principle. The sensor comprises a 100 MHz signal source, a 50Ω coaxial transmission line, detection and signal processing circuit, and a protective enclosure. The high-frequency electromagnetic waves, generated by the sinusoidal signal from signal source, propagate along the coaxial transmission line to the parallel detection ring. Due to the impedance mismatch between the detection ring and transmission line, a portion of the signal undergoes reflection, resulting in the formation of a standing wave through the superposition of incident and reflected waves. This phenomenon induces voltage amplitude variations at each point along the transmission line. The detection circuit captures the differential signal between points a and b on the transmission line, subsequently amplified by an amplifier, yielding the sensor output voltage denoted as U_{out} (Tian et al., 2022; Zhao et al., 2022):

$$U_{\text{out}} = \beta(V_a - V_b) = 2\beta A \left(\frac{Z_l - Z_0}{Z_l + Z_0} \right) \quad (1)$$

Where, U_{out} is the output voltage of the sensor; β is the amplification factor; A is the amplitude of the high-frequency signal source; Z_0 denotes the impedance of the transmission line, which is 50Ω ; Z_l signifies the impedance of the detection ring. Given that A , β , and Z_0 are constants, the output voltage U_{out} is determined by Z_l .

Some studies have shown that there is a direct correlation between the impedance of stem tissue and its internal dielectric constant (Tian et al., 2020; Tian et al., 2022). Given that the dielectric constant of water (approximately 81), significantly surpasses that of dry stem material or ice (approximately 3) (Cheng et al., 2021), noticeable variations in the dielectric constant of stem tissues occur during phenomena such as water charging and discharging or the mutual transition between liquid water and solid ice, namely freeze-thaw cycles (Zhao et al., 2021b; Tian et al., 2020). Consequently, these alterations induce conspicuous changes in Z_l , thereby leading to marked fluctuations in U_{out} (Sun et al., 2019; Tian et al., 2022; Zhou et al., 2016).

Previous experiments have consistently demonstrated a linear relationship with determination coefficients exceeding 0.96 between U_{out} and the actual value of stem water content (Tian et al., 2020; Liang et al., 2020; Zhou et al., 2018). It is essential to emphasize that the purpose of this study is to analyze variation characteristics of stem water content without necessitating the acquisition of actual values of stem water content. Therefore, it is feasible to directly employ the change of U_{out} to characterize fluctuations in water content within the stem tissue (Zhao et al., 2021; Xu et al., 2023). During sensor installation, the adjustment knob on the sensor detection ring is rotated to open the ring. The detection ring is then positioned around the tree stem at a height of approximately 1.3 meters above the ground, that is, at the breast height. Subsequently, by reversing rotation of the adjustment knob, the detection ring is snugly affixed to the tree stem. These procedures enable non-invasive, in-situ monitoring of stem water content.

2.3 Acquisition of environmental parameter and monitoring system construction

In the vicinity of the planted *Acer truncatum*, an array of sensors was strategically installed to capture diverse environmental parameters. Specifically: the BXY meteorological louver box was employed for recording air temperature and relative humidity. Simultaneously, this study introduced saturated water vapor pressure difference, calculated from air temperature and relative humidity with specific formula available in reference (Li et al., 2022); the EL15-1A wind speed sensor was used to measure wind speed; the HYSWR-ARC soil moisture sensor was employed to acquire soil moisture content; the DS18B20 temperature sensor was used for monitoring soil temperature; the GHFS photosynthetically active radiation sensor was used to measure photosynthetically active radiation; the SL3-1 rainfall sensor was used to record precipitation; To facilitate stem temperature measurement, a small hole, approximately 2mm in diameter and 8mm in length, was drilled at the breast diameter. Subsequently, a PT100 temperature sensor was inserted into the hole to capture temperature changes inside the stem, aiding in the analysis of the occurrence of liquid water to solid ice phase transition within the stem throughout the overwintering period.

To facilitate real-time and online monitoring of stem water content and various environmental parameters during the research period, we established an Internet of Things (IoT)-based multi-sensor ecological information monitoring system. Each sensor was connected to a multi-channel data collector based on the ATMEGA2560 microcontroller. Relevant data acquisition programs were developed to collect sensor data at a frequency of every 10 minutes. While the collected data were stored on the SD card, and a 4G DTU module was employed to upload the packaged sensor data via the GPRS network to a remote Alibaba Cloud server for storage. Subsequently, the data packets were transmitted to the laboratory's independently developed ecological information monitoring platform, where they underwent parsing and processing, enabling the real-time visualization and downloading of data from various sensors. Through above processes, the comprehensive *Acer truncatum*. ecological information monitoring system was ultimately successfully established. Monitoring activities commenced in early April 2022.

2.4 Data processing and analysis

An *Acer truncatum* plant, consistently maintaining robust health and providing comprehensive stem water content data throughout the monitoring period, was selected as the representative tree. The study delved into the variation characteristics of stem water content and associated influencing factors during the overwintering period, spanning from early November 2022 to early April 2023. It's essential to highlight that a power failure at the experimental site from January 15 to January 29, 2023, resulting in the loss of stem water content data and environmental data during this interval. In addition, to facilitate an in-depth exploration of stem water content variation characteristics during the overwintering period, the study categorized the period into three stages: 1) deciduous stage (from early November to the end of November); 2) dormant stage (from early December to early February); and 3) bud-breaking stage (from early February to early April).

Microsoft Excel 2019 was used for organizing the acquired environmental data and stem water content data, as well as calculating relevant parameters; The filtering algorithm in MATLAB R2022a software was employed to eliminate anomalous data arising from environmental disturbances or human factors. Pearson correlation analysis and path analysis in SPSS 20.0 were performed to analyze the relationship between stem water content and various environmental parameters. Graphical representations were generated using Microsoft Visio 2003 and Origin 2021b software.

3. Results and discussion

3.1 Variation characteristics of environmental parameters

Figure 2 illustrates the variations characteristics of environmental parameters throughout overwintering period, spanning from early November 2022 to early April 2023. The observations reveal the following characteristics: air temperature, soil temperature, and stem temperature all exhibited a declining and then increasing trend from early November to early April of the following year, that is, transitioning from the deciduous stage to the dormant stage and then to the bud-breaking stage. Specifically, air temperature ranged from -11.1°C to 28.3°C , with an average of 4.7°C ; soil temperature ranged from -7.1°C to 24.9°C , with an average of 3.6°C ; meanwhile, stem temperature fluctuated between -13.5°C and 33.2°C , with an average of 4.2°C . The daily fluctuation range of relative humidity, saturation vapor pressure deficit, and photosynthetically active radiation exhibited a trend characterized by an initial reduction succeeded by an augmentation. Among them, relative humidity ranged from 5.6–89.9%, with an average of 34.5%; saturation vapor pressure deficit fluctuated between 0.2619 kPa and 3.8415 kPa, with an average of 0.9565 kPa; photosynthetically active radiation varied from 0 to 278 W/m^2 . Soil moisture experienced freezing occurrences during the dormant stage, attributed to the decrease in both air temperature and soil temperature, leading to a diminished level; The fluctuation of soil moisture ranged from 23.76–56.12%, with an average of 36.68%. Wind speed presented a discernible pattern, escalating from the deciduous stage to the dormant stage, subsiding thereafter, and manifesting an ascending trend during the bud-breaking stage. Wind speed ranged from 0 to 52.9 m/s, with an average of 5.64 m/s.

3.2 Variation characteristics of stem water content

3.3.1 Variation characteristics of stem water content during different stages

The study integrated stem temperature to analyze the dynamics of stem water content during different stages of overwintering period, including the deciduous stage, dormant stage, and bud-breaking stage. Stem water content data and stem temperature data for a duration of 10 days were selected during each of the three stages for analysis, as depicted in Fig. 3a-c.

Figure 3a presents the variation characteristics of stem water content and stem temperature during the deciduous stage, spanning from November 1, 2022, to November 10, 2022. Both stem water content and stem temperature exhibited a "daytime ascent and nighttime descent" diurnal pattern. There existed a positive correlation between the two, signifying that heightened daily fluctuation in stem water content corresponds to increased daily fluctuation in stem temperature, and vice versa. The daily average fluctuation range of stem water content was relatively small at 38 mV, while the stem temperature exhibited a broader fluctuation range spanning from -1.8°C to 21.2°C . In most instances, stem water content experienced a gradual reduction concomitant with the decline in stem temperature during the early morning hours, typically reaching the minimum value of the day from 6:30 to 7:40, slightly preceding the nadir of stem temperature. Subsequently, as stem temperature ascended, a corresponding gradual increase

in stem water content occurred. After stem temperature generally peaked around 14:00, stem water content reached its maximum value at a closely aligned moment. Subsequent to the peak, both stem water content and stem temperature exhibited a gradual reduction until the early morning of the next day.

Figure 3b depicts the variation characteristics of stem water content and stem temperature during the dormant stage from November 30, 2022, to December 9, 2022. Analogous to the deciduous stage, both stem water content and stem temperature exhibited a diurnal "daytime ascent and nighttime descent" diurnal pattern. Notably, in contrast to the deciduous stage, stem temperature during the dormant stage underwent a substantial decrease, with a fluctuation range spanning from -10°C to 14.4°C . Generally, ambient temperature fluctuations could induce the phase transition between liquid water and solid ice within the stem tissue, resulting in noticeable alterations in the internal dielectric constant within stem tissue and corresponding variations in stem water content sensor data (Zhao et al., 2021a; Cao et al., 2023). Specifically, when a decrease in temperature induced the conversion of liquid water into solid ice within the stem tissue, the internal dielectric constant of the stem tissue experienced a significant decrease, resulting in a pronounced drop in stem water content sensor data. Conversely, an increase in temperature led to the reversion of solid ice to liquid water, causing an elevation in the dielectric constant and an increase in stem water content sensor data. Consequently, during the dormant stage, a substantial augmentation in the daily fluctuation range of stem water content was observed compared to the deciduous stage, with an average daily fluctuation of 276.5 mV.

In most instances, the reduction in stem moisture initiated in the early morning due to the continuous decline in stem temperature, resulting in the conversion of liquid water into solid ice within the stem tissue. Stem temperature reached its minimum around 7–8 a.m. The pace of decline in stem water content decelerated in the morning, reaching its minimum around 8–9 a.m., indicating the initiation of the melting process for the solid ice within the stem tissue into liquid water. As stem temperature continued to rise, reaching its peak between 14:20 – 15:00; the sustained melting of solid ice inside the stem tissue led to an increase in stem water content which reaching its maximum value at a relatively close moment. Subsequently, from around 19:00, stem water content experienced a relatively slow decline in most cases. Concurrently, stem temperature also exhibited a slow decline process after a rapid drop (marked by the blue box in the Fig. 3b). The phenomenon could be attributed to the significant drop in stem temperature inducing the freezing of liquid water within the stem tissue. The release of heat during the process of water freezing resulted in a deceleration in the rate of stem temperature decline. This phenomenon aligned well with the latent heat effect observed by Zhao et al. (2021a) and Tian et al. (2023) during water freezing within living stem tissue in laboratory environment. Subsequently, stem temperature continued to decrease until the early morning of the next day, and the majority of liquid water within the stem tissue underwent conversion to solid ice, resulting in a rapid decrease in stem water content. In addition, due to a significant elevation in stem temperature from December 7–9 compared to the earlier period, there was no pronounced freezing-thawing alternation observed in stem water content.

Figure 3c illustrates the variation characteristics of stem water content and stem temperature during the bud-breaking stage from March 23, 2023, to April 1, 2023. Both stem water content and stem temperature exhibited a diurnal "daytime ascent and nighttime descent" diurnal pattern. The average daily fluctuation range of stem water content was notably reduced compared to the dormant stage, measuring at 59.6 mV. In most cases, the reduction in stem water content commenced in the early morning as the stem temperature gradually decreased. Stem temperature reached its minimum value around 6:30 in the morning, followed by an upward trend. While stem water content, with a relative lag, reached its minimum value around 7:20 in the morning before ascending. Both stem temperature and stem water content peaked around 16:00 in the afternoon and began to decrease until the early morning of the following day.

3.2.2 Variation characteristics of stem water content during the overwintering period

Figure 4 presents the variation characteristics of stem water content and stem temperature during the overwintering period, spanning from early November 2022 to early April 2023, revealing a notable consistency between the two variables.

In the initial period from early November to the end of November, stem water content maintained a relatively elevated level with a limited daily fluctuation range. The phenomenon could be attributed to the decreasing ambient air temperatures, causing a noticeable reduction in physiological activities such as transpiration and photosynthetic carbon fixation during the deciduous stage. Additionally, the decline in xylem conductivity further contributed to the weakened intensity of water filling and discharging

inside the plant stem tissue (Partelli-Feltrin et al., 2023; Ding et al., 2021). Nonetheless, study has indicated that the recovery of root pressure contributed to an overall elevation in stem water content during this stage (Hao et al., 2013).

By November 29th, there was a significant decline in stem temperature compared to the previous stage, reaching a minimum temperature of -6.5°C. Notably, at this time, the stem tissue manifested a freezing phenomenon indicative of a pronounced reduction in stem water content. As stem temperature ascended beyond a certain threshold, the phase transition of solid ice within the stem tissue to liquid water ensued, leading to a continuous increase in stem water content. Studies have shown that the occurrence of multiple freezing-thawing cycles within stem tissue can intensify xylem embolism, consequently impeding the transport of stem water content (Song et al., 2023). Concurrently, the decrement in soil temperature reduced root activity, concomitant with a diminished capacity for water absorption, causing inadequate replenishment of water loss through plant transpiration (Aroca et al., 2012). Consequently, stem water content was overall at a lower level during this stage. The phenomenon of significant fluctuation in water content within the stem tissue due to freezing-thawing cycles persisted until early February of the subsequent year, aligning closely with the variation characteristics of stem water content during the dormant stage observed by Sun et al. (2019) and Tian et al. (2023).

Commencing from early February, with the continuous ascent in air temperature, soil temperature, and stem temperature, the solid ice content within the stem tissue gradually decreased (Zhao et al., 2021a; Zhao et al., 2021b). The freezing-thawing phenomenon gradually dissipated, resulting in a noticeable reduction in the fluctuation range of stem water content compared to the preceding period. Studies have shown that during this stage, the plant vitality gradually recovered, entering a phase characterized by embolism repair, hydraulic conductivity reconstruction, and a concurrent increase in root pressure (Beedlow et al., 2017; Bourbia et al., 2021). However, the plant transpiration activity has not yet reached its peak, signifying a relatively limited amount of water charging and discharging within stem tissue. Therefore, it could be observed that, from early February to early April, stem water content exhibited a gradually increasing trend, accompanied by a relatively small fluctuation range.

Our study revealed distinctive variation characteristics in stem water content of *Acer truncatum* during the overwintering period compared to the findings of studies on other tree species, such as *Lagerstroemia indica* and *Populus tomentosa* conducted by Zhao et al. (2021a) and Zhao et al. (2021b), which reflects the diverse adaptive capacities exhibited by different tree species in response to varying degrees of freezing-thawing stress during the overwintering period (McCulloh et al., 2023).

3.3 Influencing factors of stem water content during the overwintering period

3.3.1 Pearson correlation analysis between stem water content and environmental parameters

Pearson correlation analysis was employed to elucidate the influencing factors causing distinct characteristics observed in stem water content during three stages of the overwintering period. This study selected environmental parameters, including air temperature (T), relative humidity (RH), vapor pressure deficit (VPD), photosynthetically active radiation (PAR), soil moisture (SM), soil temperature (TS), wind speed (WS), and stem temperature (ST), for analysis. The results, presented in Table 1, demonstrated differential correlations between stem water content and environmental parameters throughout different stages of overwintering period.

Table 1
Pearson correlation analysis between stem water content and environmental parameters.

Stage	T	RH	VPD	PAR	SM	TS	WS	ST
Deciduous stage	0.932**	-0.471**	0.932**	0.533**	0.01	0.537**	0.585**	0.922**
Dormant stage	0.746**	-0.403**	0.685**	0.232**	-0.156**	0.378**	0.179**	0.906**
Bud-breaking stage	0.956**	-0.212**	0.952**	0.505**	-0.124**	0.858**	0.515**	0.967**
Note: * denotes a significant difference at the 0.05 level, and ** denotes a significant difference at the 0.01 level; T represents air temperature (°C); RH represents relative humidity (%); VPD represents vapor pressure deficit (kPa); PAR represents photosynthetically active radiation ($\text{W}\cdot\text{m}^{-2}$); SM represents soil moisture (%); TS represents soil temperature (°C); WS represents wind speed ($\text{m}\cdot\text{s}^{-1}$); ST represents stem temperature (°C).								

During the deciduous stage, stem water content exhibited positive correlations with all environmental parameters, besides relative humidity. Specifically, stem water content showed highly significant positive correlations with T, VPD, and ST, aligning well with the primary influencing factors for stem water content studied by Beedlow, et al (2017) during the deciduous stage. Following in importance were WS, TS, PAR, and RH. Stem water content exhibited the weakest correlation with SM, with a coefficient of only 0.01. This could be attributed to the weakened physiological activities of plants during the deciduous stage, resulting in a noticeable reduction in the amount of water charging and recharging within the stem tissue compared to the growth period (Wang et al., 2021); Despite stem water content predominantly originating from SM, an increase in SM did not necessarily elevate stem water content; leading to a conspicuous weakening of the correlation between the two.

Transitioning into the dormant stage, stem water content exhibited its strongest correlation with ST, indicating that ST was the predominant factor determining the freezing-thawing alternation of stem water content during this stage. Despite a weakening in the correlations between stem water content and T, VPD, PAR, TS, and WS, they remained highly significant. The relationship between stem water content and SM shifted from a weak positive correlation to a significantly negative correlation. Data analysis revealed that the transition occurred when TS reached its peak during the dormant stage (around 19–20 pm), significantly lagging behind the peak of stem water content (around 14pm). Consequently, as stem water content reached its peak and began to decline, SM continued to increase due to the rising TS, resulting in a negative correlation between the two.

During the bud-breaking stage, noticeable increases in correlations between stem water content and T, VPD, ST, PAR, and TS were observed. This corresponds to the gradual enhancement of above environmental parameters, facilitating the resurgence of plant vitality and the cessation of freezing-thawing phenomena in stem water content. Elevated TS enhanced root activity, increasing root water absorption capacity (Kumar et al., 2022), and induced SM melting; Simultaneously, as stem water content primarily originates from SM, resulting in the gradual attenuation of the negative correlation between stem water content and SM. These factors collectively contributed to the gradual rise in stem water content during the bud-breaking stage. In addition, increased WS during this stage accelerated the plant inherent transpiration, aiding in the upward water transport from the roots to the stem tissue (Zhang et al., 2021), thereby contributing to the elevation in stem water content. Additionally, the correlation between stem water content and RH exhibited a decline trend.

3.3.2 Path analysis of stem water content and environmental parameters

In addition to Pearson correlation analysis, the study further clarified the impact and magnitude of various environmental parameters on stem water content during the three stages of overwintering period by employing path analysis. The results are presented in Tables 2–4.

Table 2
Path analysis of environmental parameters on stem water content during the deciduous stage

Environmental factors	Direct path coefficient	Indirect path coefficient								
		T	RH	VPD	PAR	SM	TS	WS	ST	Total
T	-0.111	-	0.0719	-0.1097	-0.0616	-0.0059	-0.0615	-0.0689	-0.1023	-0.338
RH	0.239	-0.1126	-	-0.1554	-0.1205	-0.0667	-0.0755	-0.1479	-0.1491	-0.8277
VPD	0.604	0.5968	-0.3926	-	0.3491	0.0248	0.3292	0.3835	0.5623	2.4499
PAR	-0.023	-0.0127	0.0116	-0.0133	-	-0.0019	0.001	-0.0128	0.0123	-0.0158
SM	-0.078	-0.0041	0.0218	-0.0032	-0.0064	-	-0.0191	-0.0109	-0.0179	-0.0398
TS	-0.104	-0.0576	0.0329	-0.0567	0.0047	0.0255	-	-0.0266	-0.0692	-0.147
WS	0.045	0.0279	-0.0278	0.0286	0.025	0.0063	0.0152	-	0.0278	0.103
ST	0.684	0.6471	-0.4268	0.6368	0.3652	0.1559	0.4549	0.422	-	2.2551
Note: T represents air temperature (°C); RH represents relative humidity (%); VPD represents vapor pressure deficit (kPa); PAR represents photosynthetically active radiation (W.m^{-2}); SM represents soil moisture (%); TS represents soil temperature (°C); WS represents wind speed (m.s^{-1}); ST represents stem temperature (°C).										

Table 3
Path analysis of environmental parameters on stem water content during the dormant stage.

Environmental factors	Direct path coefficient	Indirect path coefficient								
		T	RH	VPD	PAR	SM	TS	WS	ST	Total
T	1.011	-	-0.5297	0.9938	0.5176	-0.3761	-0.003	0.2295	0.8927	1.7248
RH	-0.053	0.0278	-	0.0268	0.0237	0.0133	0.0063	0.0340	0.0225	0.1544
VPD	-1.266	1.2444	0.6393	-	-0.6621	0.4659	0.0127	-0.2924	-1.0912	0.3166
PAR	0.106	0.0542	-0.0475	0.0554	-	-0.01	-0.0213	0.0345	0.0299	0.0952
SM	-0.079	0.0294	0.0198	0.0291	0.0071	-	-0.0508	-0.0266	0.0224	0.0304
TS	0.176	-0.0005	-0.0208	-0.0018	-0.0354	0.1132	-	0.0213	0.0463	0.1223
WS	-0.01	-0.0027	0.0064	-0.0023	-0.0033	-0.0034	-0.0012	-	-0.0019	-0.0084
ST	0.986	0.8706	-0.4191	0.8499	0.2781	-0.28	0.2593	0.1893	-	1.7481
Note: T represents air temperature (°C); RH represents relative humidity (%); VPD represents vapor pressure deficit (kPa); PAR represents photosynthetically active radiation (W.m^{-2}); SM represents soil moisture (%); TS represents soil temperature (°C); WS represents wind speed (m.s^{-1}); ST represents stem temperature (°C).										

Table 4
Path analysis of environmental parameters on stem water content during the bud-breaking stage.

Environmental factors	Direct path coefficient	Indirect path coefficient								
		T	RH	VPD	PAR	SM	TS	WS	ST	Total
T	-0.316	-	0.0373	-0.3109	-0.1296	0.0872	-0.2724	-0.1390	-0.3056	-1.033
RH	0.089	-0.0189	-	-0.0122	-0.0328	-0.0669	-0.0025	-0.0536	0.0232	-0.1637
VPD	0.448	0.4408	-0.0614	-	0.1850	-0.1147	0.3808	0.1958	0.4225	1.4488
PAR	0.203	0.0832	-0.0747	0.0838	-	0.0213	0.0156	0.0999	0.0932	0.3223
SM	0.068	-0.0188	-0.0511	-0.0174	0.0071	-	-0.0126	0.0249	-0.0083	-0.0762
TS	0.296	0.0414	0.0511	0.0175	0.0239	0.0109	-	0.1448	0.2483	0.5379
WS	0.003	0.0013	-0.0018	0.0013	0.0015	0.0011	0.0009	-	0.0016	0.0059
ST	0.538	0.5202	-0.1404	0.5073	0.2469	-0.0656	0.4514	0.2868	-	1.8066
Note: T represents air temperature (°C); RH represents relative humidity (%); VPD represents vapor pressure deficit (kPa); PAR represents photosynthetically active radiation ($\text{W}\cdot\text{m}^{-2}$); SM represents soil moisture (%); TS represents soil temperature (°C); WS represents wind speed ($\text{m}\cdot\text{s}^{-1}$); ST represents stem temperature (°C).										
(a) Variation characteristics of stem water content and stem temperature during the deciduous stage										

Table 2 shows that during the deciduous stage, the direct path coefficients (direct effects) of environmental parameters on stem water content, arranged in descending order: ST, VPD, RH, T, TS, SM, WS, and PAR; Notably, RH, VPD, WS, and ST demonstrated direct positive effects on stem water content. The indirect path coefficients revealed that VPD and ST exerted a substantial indirect influence on stem water content through interactions with other environmental parameters. Specifically, VPD exerted its influence on stem water content through the combined effects of T, ST, WS, PAR, and TS. ST primarily affected stem water content through the combined effects of T, VPD, TS, RH, WS, and PAR.

Entering into the dormant stage, it could be observed from Table 3 that the direct path coefficients of environmental parameters impacting stem water content, ranked in descending order as follows: VPD, T, ST, TS, PAR, SM, RH, and WS. To elaborate, T, ST, TS, and VPD exhibited direct positive impacts on stem water content, whereas the remaining parameters demonstrated direct negative effects. The indirect pathway coefficients revealed that T and ST exerted a significant indirect influence on stem water content through interactions with other environmental parameters. Specifically, T primarily influenced stem water content through the combined effects of VPD, ST, PAR, and RH. While ST exerted its influence through the combined effects of T, RH, VPD, and TS.

It could be seen from Table 4 that the direct path coefficients of environmental parameters affecting stem water content during the bud-breaking stage, ranked in descending order: ST, VPD, T, TS, PAR, RH, SM, and WS. All factors, with exception of T, exhibited direct positive effects on stem water content. By analyzing the indirect path coefficients, T, VPD, and ST exerted a significant indirect influence on stem water content through interactions with other environmental parameters. Specifically, T chiefly affected stem water content through the combined effects of VPD, ST, and TS. The rationale behind the direct and indirect negative effects of air temperature on stem water content warrants further investigation. VPD determined stem water content through the combined effects of T, TS, and ST. ST exerted its influence on stem water content through the collective impacts of T, VPD, and TS.

4. Conclusion

In this paper, we developed an Internet of Things (IoT)-based ecological information monitoring system for *Acer truncatum*, providing real-time and online access to stem water content and environmental parameters. The variation characteristics of stem water content were captured through an independently designed stem water content sensor based on the standing wave ratio principle, facilitating in-situ and non-destructive data acquisition.

Stem water content during the overwintering period exhibited a diurnal pattern of "daytime ascent and nighttime descent". During the deciduous stage, the daily fluctuation range of stem water content was relatively small, reaching a minimum around 6–7 a.m. and a maximum around 2 p.m. During the dormant stage, stem water content underwent a freezing-thawing alternation, characterized by the transformation between liquid water and solid ice, resulting in a significantly increased daily fluctuation range; The minimum occurred around 8–9 a.m., and the maximum around 2–3 p.m. During the bud-breaking stage, the freezing-thawing alternation disappeared, leading to a notable reduction in the daily fluctuation range, with a minimum around 7 a.m. and a maximum around 4 p.m. Stem water content generally remained at a higher level from early November to the month's end; From early December to early February of the subsequent year, it experienced a freezing-thawing cycle, followed by a gradual increase until the end of overwintering period.

Pearson correlation coefficients between environmental parameters and stem water content exhibited temporal variations across different stages. Path analysis indicated differences in the impact and magnitude of environmental parameters on stem water content: during the deciduous stage, VPD and ST played a significant role; during the dormant stage, T, VPD, and ST emerged as the dominant factors; during the bud-breaking stage, ST significantly contributed to stem water content.

In conclusion, the study provides a feasible approach and favorable conditions for exploring plant stem water content and its influencing factors during the overwintering period, which is crucial for a better understanding of the winter survival, adaptation, and subsequent growth and development of forest trees.

Declarations

Acknowledgments

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Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

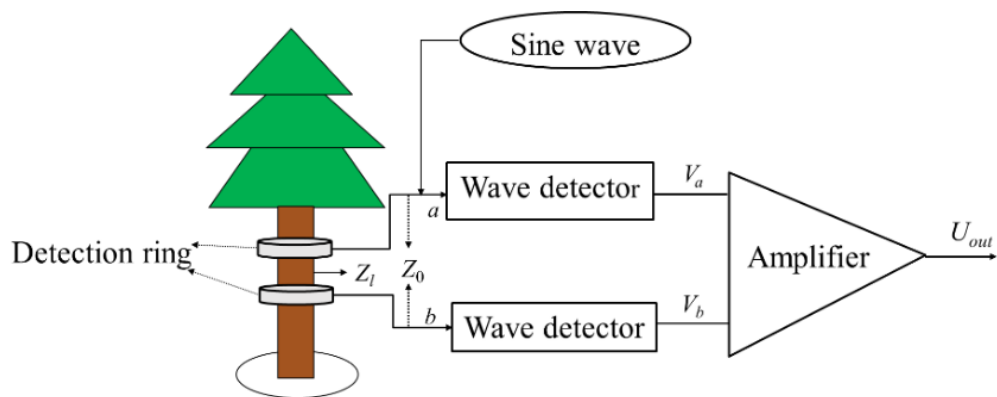
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Figures



(a) Schematic diagram of stem water content



(b) The physical image of stem water content

Figure 1

The schematic diagram and physical image of stem water content. (a) schematic diagram of stem water content; (b) the physical image of stem water content.

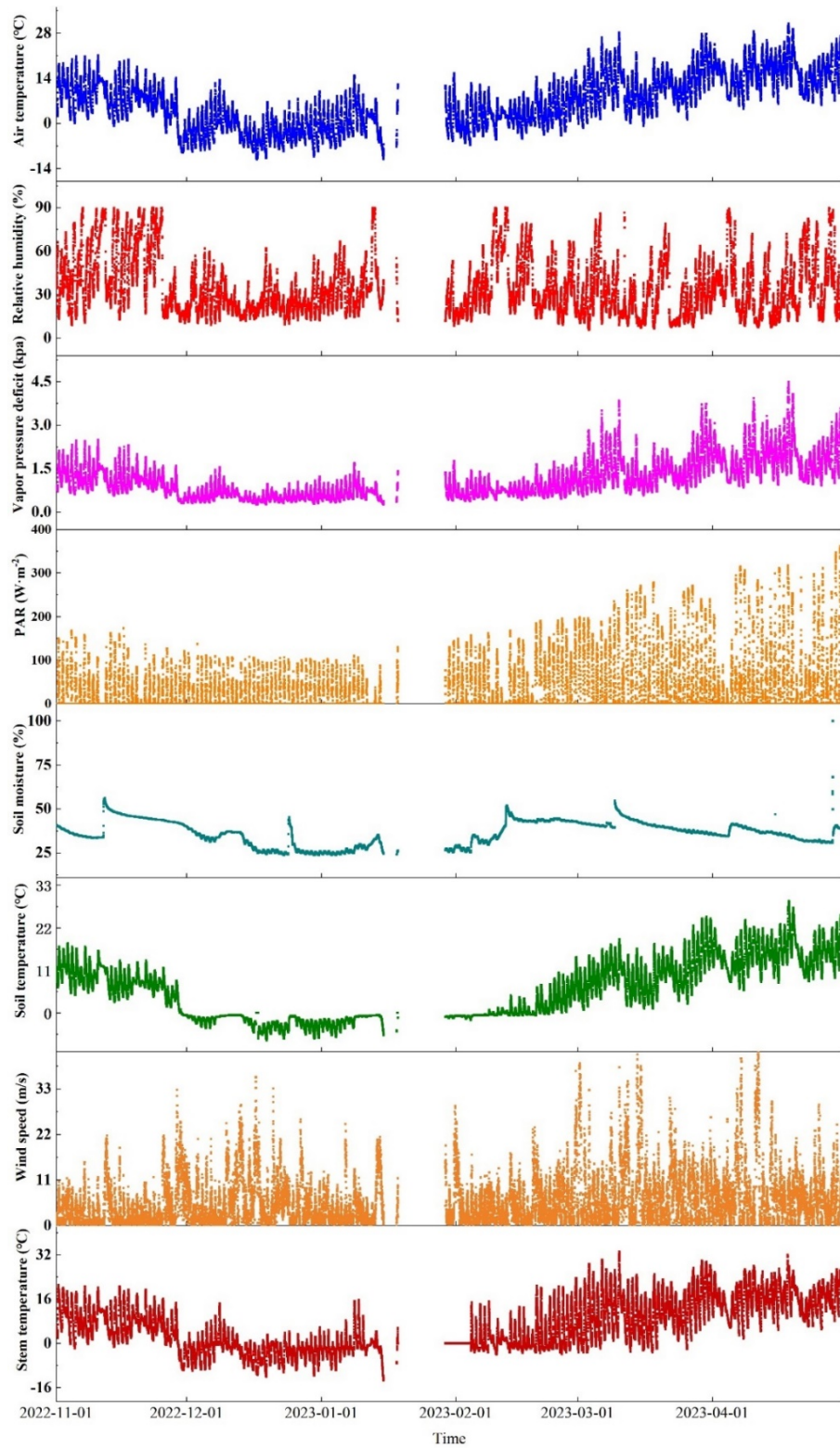
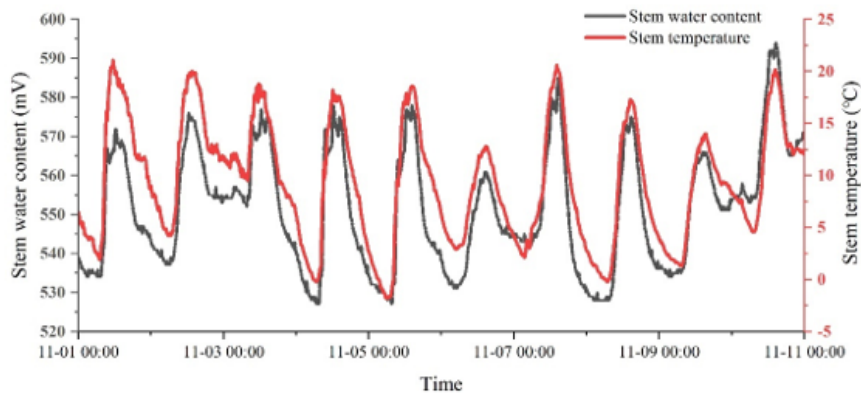
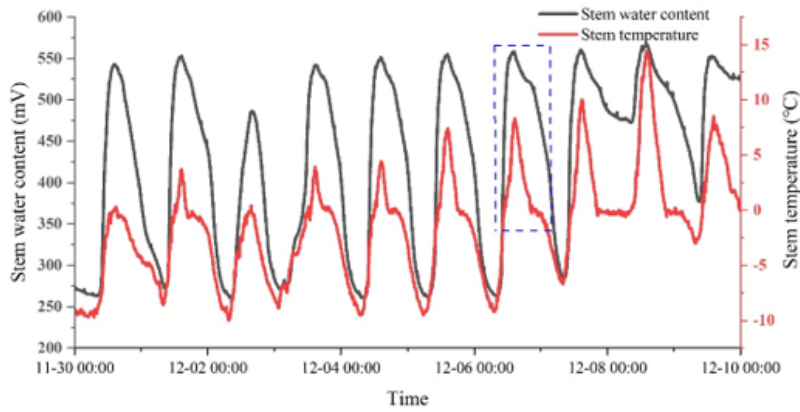


Figure 2

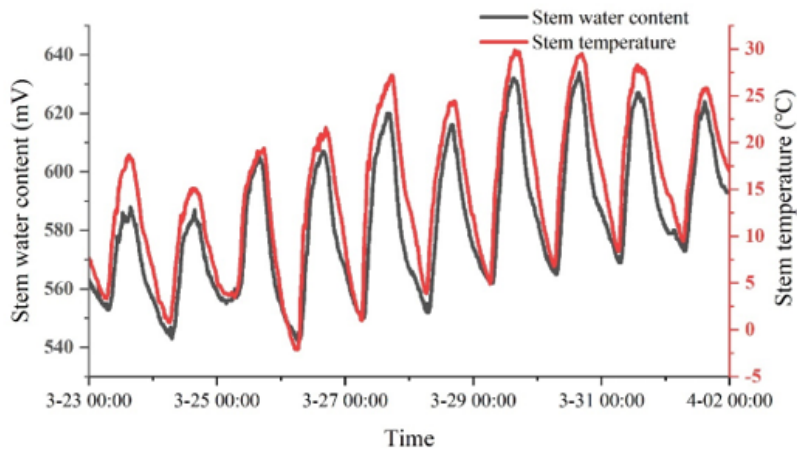
Variation characteristics of environmental parameters throughout overwintering period.



(a) Variation characteristics of stem water content and stem temperature during the deciduous stage



(b) Variation characteristics of stem water content and stem temperature during the dormant stage



(c) Variation characteristics of stem water content and stem temperature during the bud-breaking stage

Figure 3

Variation characteristics of stem water content and stem temperature during different stages of the overwintering period.

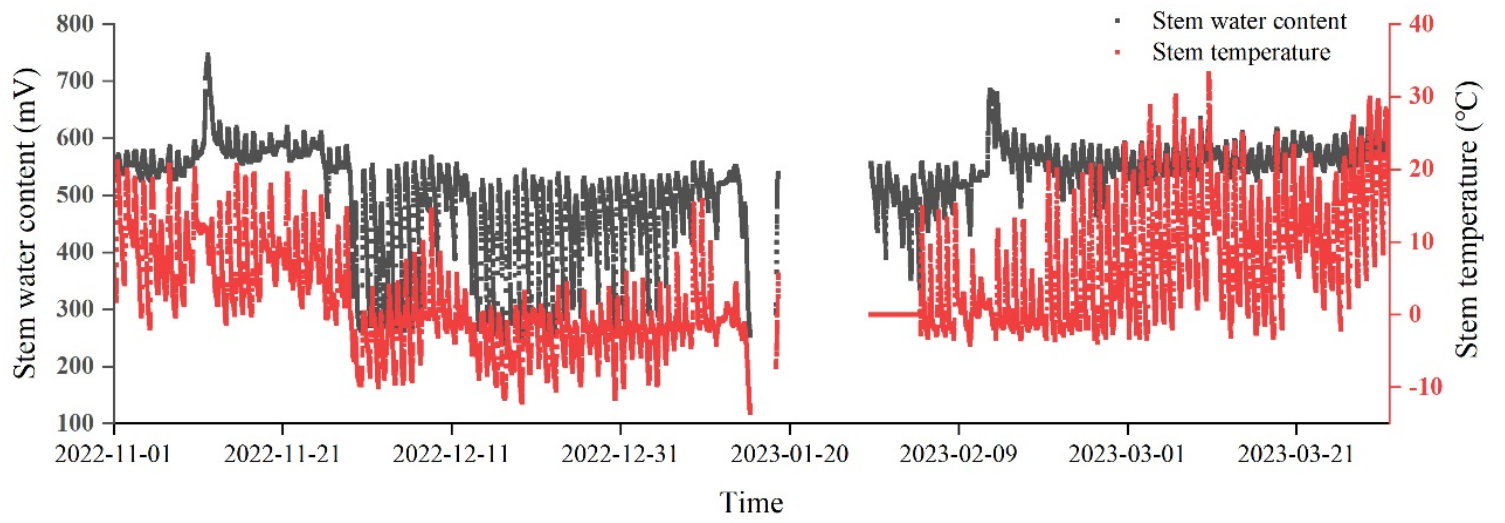


Figure 4

Variation characteristics of stem water content and stem temperature during the overwintering period.