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Assessing the Vitality Status of Plants: Using the Correlation between Stem Water Content and External Environmental Stress

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Abstract: Plant vitality is an important indicator of plant health. Previous studies have often assessed plant vitality using related physiological parameters, but few studies have examined the effects of changes in plant vitality on stem water content (StWC), which can be measured online, in real time, and nondestructively using a novel fringing impedance sensor. In the present study, the sensor calibration results showed a linear fitting relationship between the sensor output voltage and StWC, with coefficients reaching 0.96. The coefficients of correlations between StWC and four plant physiological parameters related to plant vitality (net photosynthetic rate, transpiration rate, stomatal conductance, and intercellular carbon dioxide concentration) were more than 0.8, indicating that StWC can be used to characterize plant vitality to a certain extent. A comparison between plants with normal vitality and weakened vitality showed that the self-regulation ability of plants gradually weakened as the plant vitality decreased, the diurnal mean of StWC lowered, and the diurnal range of StWC increased. In conclusion, StWC can be used as a new parameter to assess plant vitality.

Keywords: plant vitality; inner fringing impedance; sensor; stem water content; external environmental stress

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1. Introduction

Plants are continuously exposed to various abiotic and biotic stresses in natural and agricultural settings. When plants are subjected to certain stresses, their vitality gradually decreases, and plants can die in severe cases. Therefore, a timely assessment of plant vitality is important for preventing plant death.

Plant physiological parameters such as net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and intercellular carbon dioxide concentration (Ci) are important internal factors that affect plant vitality. Previous studies have shown that changes in plant viability can be assessed by measuring these plant physiological parameters. Shangguan et al. showed that plant Pn decreased greatly when plant life and health were impaired [1]. Ephrath, J. et al. found that Pn decreased when maize vitality was weakened owing to water shortage [2]. Ploetz et al. reported that avocado (*Persea americana* Mill) infected with *Raffaelea lauricola* sp. nov. had significantly lower Pn, Gs, Tr, water use efficiency, and xylem sap flow rate than noninfected trees [3]. Pegoraro et al. found that Ci decreased when plant vitality was lowered owing to drought or water stress [4].

Healthily growing plants have certain regulatory capabilities; however, when plants are in an unhealthy state, their vitality decreases and self-regulation ability reduces, leading to abnormal changes in their physiological parameters. The healthy status of plants can be assessed by detecting such changes in plant physiological parameters [5].

As the most important constituent in plants, water is involved in all plant life activities [6]. Plant water content significantly affects plant health; conversely, a decline in plant vitality causes abnormal changes in plant water content [7,8].

Johnson and Tyree study surface that sap exudation is reduced when stem water content (StWC) is at a high level [9]. Cao et al. showed that stem diameter, water content, and freezing–thawing are several important factors influencing the development of bacterial ulcer disease in fruit trees [10]. Wullschleger et al. noted that measurements of plant water can be used to quantitatively estimate whole-plant water in trees, which is important for studying transpiration and hydraulic conductivity in plants and guiding irrigation water use [11]. Zweifel et al. showed that diurnal variation in StWC reflects the daily water storage status of plants, and that good plant water storage dynamics not only contribute to daily transpiration but also play an important role during drought [12]. These studies further illustrate the close role of plant water in plant growth, but most research studies have assessed plant vitality on the basis of plant physiological parameters, few studies have examined the effect of changes in plant vitality on plant water content. In the present study, we designed an electromagnetic wave inner fringing impedance (EWIFI) sensor for StWC and analyzed the sensor performance. We selected *Lagerstroemia indica* L., *Pinus sylvestris* var. *mongholica* Litv, *Malus micromalus* Makino and *Pinus tabuliformis* Carriere for the experiments, the relationship between StWC and various physiological parameters shows that StWC has obvious correlation with plant physiological parameters and can be used to characterize plant vitality; and by comparing and analyzing the changes in StWC under different vitality states, the results show that when plant vitality decreases, StWC also changes, so StWC can be used to assess plant vitality. By monitoring StWC online in real time through EWIFI sensors, the dynamic changes in plant vitality can be obtained, and the plant growth status can be assessed in real time for timely related management.

2. Materials and Methods

2.1. Measuring StWC Using EWIFI Sensor

Tree stem is mainly composed of water and wood. The dielectric constant of water is approximately 81 and the dielectric constant of wood is approximately 3 [13,14]; thus, the dielectric constant of tree stems changes with the varying water content in them [15]. When the probe is installed at the stem, a change in the dielectric constant of the stem leads to a change in the probe impedance. As shown in Figure 1, when the electromagnetic wave generated by the oscillating source is transmitted to the probe along the transmission line, the impedance of the plant tissue inside the probe does not match the impedance of the probe, and the electromagnetic wave is reflected from the inner edge of the probe [16–18]. The impedance of the probe can be estimated by measuring the incident and reflected waves of the probe. Therefore, we designed an EWIFI sensor to measure StWC. The sensor mainly includes a 100 MHz electromagnetic wave oscillation signal source, a 50 Ω coaxial transmission line, a bimetallic ring probe, two signal wave detectors, and a signal amplifier. The sensor output voltage (U) can be computed using Equation (1) as follows:

$$U = \beta(U_1 - U_2) = 2\beta A\rho = 2\beta A\frac{Z_P - Z_L}{Z_P + Z_L}, \tag{1}$$

where β is the amplification factor of the amplifier; U_1. and U_2 are the output voltages at the two ends of the transmission line measured by wave detectors; A is the electromagnetic wave amplitude; ρ is the reflection coefficient; and Z_P is the transmission line and probe impedance, which is determined by transmission impedance, probe size, and electromagnetic wave frequency; when the transmission line, probe size, and wave frequency are fixed, Z_P is a fixed value. Z_L is the plant impedance at the probe. Among all the parameters, only the Z_L is undetermined, a change in Z_L. is reflected in the output voltage magnitude.

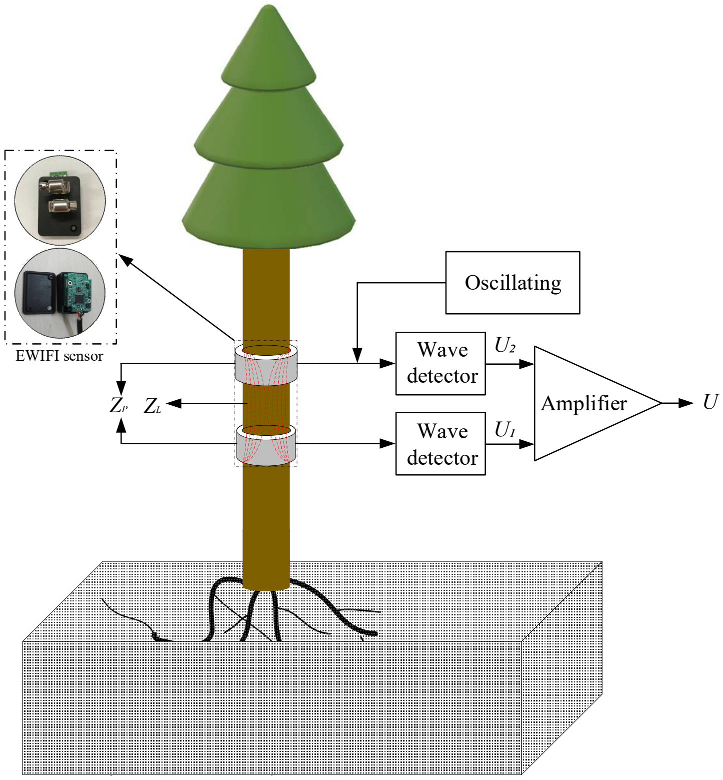

Figure 1. Schematic diagram of the electromagnetic wave inner fringing impedance (EWIFI) sensor. Sensor output voltage (U), output voltage at both ends of transmission line (U_1 and U_2), transmission line and probe impedance (Z_P), plant impedance at the probe (Z_L).

The EWIFI sensor mainly includes the measurement circuit board, adjustable annular probe, and shell. The adjustable annular probe consists of two metal rings made of American Society for Testing Materials 304 stainless steel; the ring diameter can be selected by adjusting a rotary knob. Each ring is connected to the measuring circuit board using a screw bolt. The shell is made of resin with a lower dielectric constant. The EWIFI sensor output voltage analog signal can be used to calculate the corresponding StWC after calibration.

2.2. *Artificial Cultivation of Lagerstroemia indica* L.

The site was located in a nursery (116°20′43.62″ E, 40°0′41.9″ N) in Haidian District, Beijing. The study area has a temperate monsoon climate with warm summers and cold winters. The main soil type is clay loam with hydrogen ion concentration (pH) values ranging from 7 to 8. Since 2018, the mean annual air temperature has been 12.6 °C, and the mean maximum and minimum annual air temperatures have been 36.5 and −12.8 °C, respectively. The mean annual precipitation was 620 mm, and the mean annual sunshine duration was 2569 h. A large number of *Lagerstroemia indica* L. were planted in the nursery (Figure 2a). After a year of artificial cultivation, some healthy trees with similar morphological characteristics (approximately 2.5 m in height, 0.04 cm in diameter at breast height, and 1 m^2 in crown projection area) were selected as experimental subjects. Some of these trees were artificially infested with pests (*Eriococcus legerstroemiae* Kuwana) to weaken their vitality, whereas others were regularly sprayed with an insecticide to maintain their healthy growth. A healthy tree used in the experiment is shown in Figure 2a and a diseased tree is shown in Figure 2b.

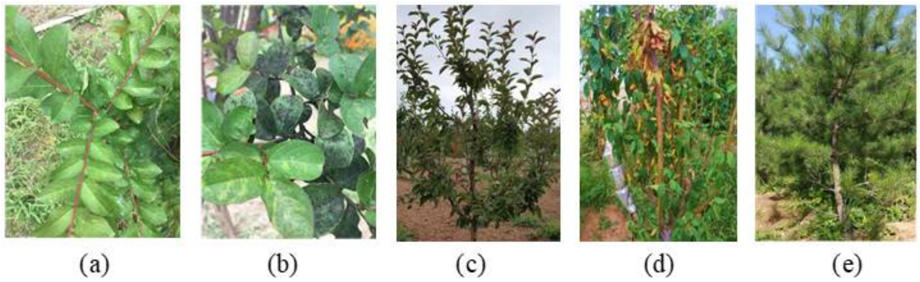

Figure 2. (**a**) *Lagerstroemia indica* L. growing healthily; (**b**) *Lagerstroemia indica* L. artificially infested with pests in July 2019; the lesion area on the trunk or leaves was more than 50%; (**c**) *Malus micromalus* Makino under normal watering conditions.; (**d**) *Malus micromalus* Makino under drought stress (26 June 2019); (**e**) *Pinus tabuliformis* Carriere.

2.3. *Pinus sylvestris* var. *mongholica* Litv *Growing in Natural Conditions*

The site was located in the Hailaer National Forest Park in Inner Mongolia (119°42′26.91″ E, 49°11′40.50″ N); the total area of the Forest Park is 1.4×10^8 m^2 and the water area is 1.333×10^7 m^2. The total number of natural *Pinus sylvestris* var. *mongholica* Litv in the park is more than 4600. The elevation of the park ranges from 612 m to 709 m. The study area belongs to the semi-arid continental grassland climate in the middle temperate zone. The lowest monthly average temperature is −30.83 °C, and the highest monthly average temperature is 25.84 °C. The average annual sunshine hours are 2800 h. The study was conducted on *Pinus sylvestris* var. *mongholica* Litv growing in natural conditions; the tree diameter was approximately 0.1 m. The trees in the first experimental group were divided into trees with and without emergence holes (Table 1). The trees in the second experimental group were divided into healthy trees, trees with a few green leaves, trees with dead leaves, and leafless trees (Table 2).

Table 1. Canopy color and symptoms of the first group of *Pinus sylvestris* var. *mongholica* Litv.

Category	Canopy Color	Symptom
No emergence holes	Green	No sign of *Sirex noctilio* Fabricius
With emergence holes	Reddish	A few emergence holes and reddish needles

Table 2. Canopy color and symptoms of the second group of *Pinus sylvestris* var. *mongholica* Litv.

Category	Canopy Color	Symptom
Healthy tree	Green	No sign of *Sirex noctilio* Fabricius
Tree with a few green leaves	Green	A few green leaves in the canopy
Tree with dead leaves	Red	Canopy becomes red
Leafless tree	Gray	Canopy with no needles

2.4. *Malus micromalus Makino in Pots Undergoing Drought Stress*

The site is located in the center of Dongsheng Garden in Beijing (116°20′13.15″ E, 40°0′42.67″ N), the elevation of the site is about 50 m, the average temperature is about 12.8 °C, and the annual sunshine hours are about 2560 h, which belongs to temperate monsoon climate. The average diameter of the stem of the potted *Malus micromalus* Makino was about 0.045 m, and the diameter and height of the pot were 0.7 m and 0.6 m, respectively. Two similar and good-growing *Malus micromalus* Makino were selected as experimental subjects from 11 June 2019 to 26 June 2019, one plant was irrigated normally (50 mL of water per day) and one plant was not irrigated during the experimental time and the pots of both trees were covered with cling film to ensure that water dissipation was only consumed through plant transpiration. The normal watered and drought-stressed *Malus micromalus* Makino are shown in Figure 2c,d.

2.5. Pinus tabuliformis Carriere Undergoing Freeze–Thaw Stress

The site is located in Hohhot City Nursery, Inner Mongolia (111°51′53.96″ E, 40°26′33.66″ N), with a site elevation of about 1115 m and an average annual temperature of about 6.2 °C. The average temperature in January is −12.8 °C and the extreme minimum temperature is −31.7 °C, the average temperature in July is 22.1 °C and the extreme maximum temperature is 37.9 °C, which belongs to the middle temperate semi-arid continental monsoon climate with long and cold winters and short and warm summers. The study was conducted on artificially planted *Pinus tabuliformis* Carriere in a nursery with a diameter of about 0.04 m (Figure 2e), and the experiment was conducted from 1 September 2017 to 16 February 2018.

2.6. Measurement of Physiological Parameters and Stem Water Content

Plant physiological parameters such as Pn, Tr, Gs, and Ci are internal factors that affect the regulation of plant water status. The four physiological parameters were synchronously measured and recorded using a LI-6400XT portable photosynthesis system (LI-COR Nebraska, America, carbon dioxide (CO_2) range 0–3100 µmol mol^{-1}, CO_2 accuracy ± 10 µmol mol^{-1}, water (H_2O) range 0–75 mmol mol^{-1}, H_2O accuracy ± 1 mmol mol^{-1}). Because Pn measured by the LI-6400XT system only represents the leaf transpiration rate, the whole-tree transpiration was measured by electronic balance (UWA-T-030, LangKe XingYe Weighting Equipment Ltd., Shanghai, China, range 0–30 kg, accuracy ± 1 g).

The stem water content was monitored using the EWIFI sensor; the performance indexes of EWIFI sensor were as follows: allowable maximum stem diameter ≤ 0.1 m, measuring range for StWC 0–100%, measuring accuracy ± 0.5%. The data, including StWC, were collected using the self-developed data logger (8 MB flash, 16-channel and 12-bit analog-to-digital converter (ADC), 0–2.5 V range, 2-channel RS-232, 2-channel RS-485) at intervals of 10 min.

2.7. Calibration of EWIFI Sensor and Comparison of Plant Physiological Parameters

Stems of *Lagerstroemia indica* L. (diameter: 0.042 m, height: 0.112 m), *Malus micromalus* Makino (diameter: 0.04 m, height: 0.105 m), *Pinus tabuliformis* Carriere (diameter: 0.04 m, height: 0.11 m), and *Pinus sylvestris* var. *mongholica* Litv. (diameter: 0.075 m, height: 0.12 m) were collected from the study sites and brought back to the laboratory. The stems were soaked in pure water for 48 h until they were completely saturated with water (purified water). The volume of the stem samples was measured by the overflow method; then, the EWIFI sensor was installed on the stem samples. The samples were weighed using precision electronic weighing and dried in a drying chamber (at 45 °C). The output voltage of the EWIFI sensor was recorded every hour, and the water lost from the stem sample was calculated on the basis of the change in weight of stem; the sample StWC corresponding to the voltage value was obtained. Finally, the EWIFI sensor was calibrated by fitting a relationship between the voltage and StWC.

The LI-6400XT system was used to measure four typical physiological parameters of healthy *Lagerstroemia indica* L. on a typical summer day; the changes in the physiological parameters between 6:00 and 18:00. were recorded. Simultaneously, the changes in StWC of *Lagerstroemia indica* L. on the same day were measured with the EWIFI sensor. The feasibility of the standard plant life activity of StWC was verified by comparing responses of physiological parameters and StWC to plant life activities.

2.8. Response of Stem Water Content to Changes in Plant Vitality

The EWIFI sensors were installed on the stem of *Lagerstroemia indica* L., *Pinus sylvestris* var. *mongholica* Litv, *Malus micromalus* Makino, and *Pinus tabuliformis* Carriere, and measured the data automatically every 10 min with the data collector. The changes in StWC of *Lagerstroemia indica* L., *Malus micromalus* Makino, and *Pinus tabuliformis* Carriere with different vitality levels were compared using the measured data. For *Lagerstroemia indica* L., healthily growing trees represented normal vitality conditions, whereas trees infested with insect pests represented weakened vitality conditions. For *Malus micromalus* Makino, normally watered trees represented normal vitality conditions, whereas trees infested with drought stress represented weakened vitality conditions. For *Pinus tabuliformis* Carriere, before entering the overwintering period, the trees are not subjected to freeze–thaw stress, which represents a normal vitality condition, while after entering the overwintering period the temperature drops and the trees are subjected to freeze–thaw stress, which represents a weakened vitality condition.

Furthermore, we measured the changes in StWC in one day in two groups of *Pinus sylvestris* var. *mongholica* Litv. In the first group, the trees without emergence holes represented normal vitality conditions, whereas the trees with emergence holes suggesting damage by pests (*Sirex noctilio* Fabricius) represented weakened vitality conditions. In the second group, *Pinus sylvestris* var. *mongholica* Litv was divided into four different health categories representing different levels of vitality. The changing curves and diurnal range of StWC were investigated under normal and weakened plant vitality levels, and a feasible method to evaluate stem moisture in order to assess plant vitality was provided.

3. Results

3.1. Calibration of the EWIFI Sensor

The calibration of the EWIFI sensor was achieved by fitting a relationship between StWC and the EWIFI sensor output voltage. The results are shown in Table 3, there was a good linear relationship between the voltage value and the volumetric stem liquid water content, the coefficient of decision of the one-time fitting decision equation reached 0.96 or more, and the K and B values of the fitting equation were used as the calibration coefficients for the different tree species in the experiment, and StWC can be calculated by fitting the curve.

Table 3. Fitting equation of value of stem water content (θ) and U.

Tree Species	Fitting Equation	R^2	K	B
Lagerstroemia indica L.	$\theta = 57.91U - 9.66$	0.9620	57.91	−9.66
Pinus sylvestris var. *mongholica* Litv	$\theta = 43.28U - 1.29$	0.9662	43.28	−1.29
Malus micromalus Makino	$\theta = 63.60U - 0.65$	0.9653	63.60	−0.65
Pinus tabuliformis Carriere	$\theta = 49.05U - 2.69$	0.9853	49.05	−2.69

Value of stem water content (θ), it is the ratio of the volume of water to the total volume of the stem (volumetric water content).

3.2. Relation between Physiological Parameters and Stem Water Content of *Lagerstroemia indica* L.

The correlations between StWC and physiological parameters were analyzed under unstressed conditions on a typical summer day (Table 4). Correlation analysis suggests that Pn, Tr, and Gs were significantly negatively correlated with StWC, and Ci was significantly positively correlated with StWC. The coefficients of correlations between StWC and the four physiological parameters were greater than 0.8, indicating a high correlation. The reason for the difference may be that the physiological parameters directly affect StWC [19,20]. In addition, we further analyzed the diurnal variation rules for StWC and the four physiological parameters (Figure 3). There was an evident decline in Pn and Gs at midday, resulting in an increase in Ci and a decrease in Tr. Furthermore, StWC also increased at midday [21,22]. The above analysis suggests that StWC can be used to characterize plant vitality to a certain extent.

Table 4. Correlations between stem water content (StWC) and four physiological parameters of *Lagerstroemia indica* L. under unstressed conditions on a typical summer day.

Variables		Physiological Parameters			
		Pn	**Tr**	**Gs**	**Ci**
StWC	Correlation coefficient	−0.8402	−0.8374	−0.8535	0.9457
	Significance probability	0.0003	0.0004	0.0002	0.0000
	Sample size	13	13	13	13

Stem water content (StWC), net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), intercellular carbon dioxide concentration (Ci).

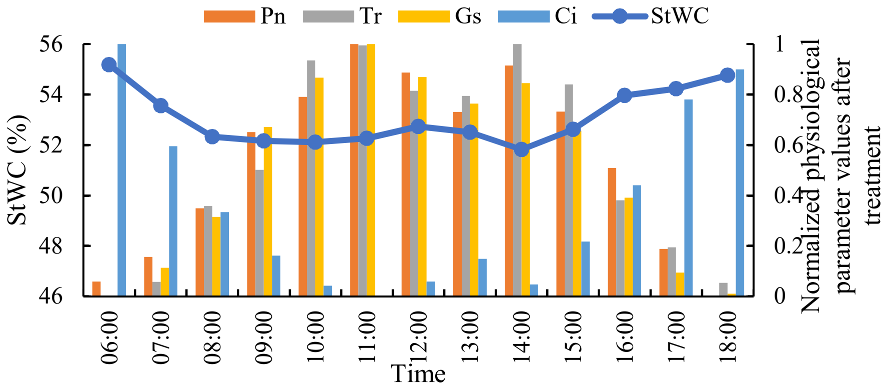

Figure 3. Diurnal variation rules of StWC and environmental parameters Pn, Tr, Gs, and Ci of *Lagerstroemia indica* L. under unstressed conditions on a typical day in summer, the results of Pn, Tr, Gs, and Ci were normalized to facilitate the observation of correlation patterns.

3.3. Comparison of Stem Water Content Parameters among Artificially Cultivated Lagerstroemia indica L.

The changes in StWC of *Lagerstroemia indica* L. under different health conditions are depicted in Figure 4. In the long term, the diurnal mean StWC of healthy trees first decreased and then increased. However, the diurnal mean StWC of severely diseased trees decreased all the time. For a better understanding of the effects of weakened plant vitality owing to diseases on StWC, we further analyzed the diurnal variation rule of StWC under disease stress. The diurnal minimum, maximum, mean, and range of StWC were selected as feature parameters to represent the diurnal variation rule of StWC. The means and standard deviations of the four feature parameters measured on June 1 among the different health level groups are shown in Figure 5. The diurnal minimum, maximum, and mean of StWC showed a positive correlation with the group health levels, and the diurnal range of StWC showed a negative correlation with the group health levels. Furthermore, the effects of disease on the four feature parameters were tested using one-way analysis of variance. As Table 5 shows, the four feature parameters differed significantly ($p < 0.001$) among different health level groups, indicating that tree health status can be diagnosed by analyzing the four feature parameters. The effects of disease on StWC also can be interpreted based on plant physiology. The lesions caused by diseases can induce tylosis formation, which reduces hydraulic conductivity, xylem function [23], and water transport [24] in affected stems and weakens the plant vitality, ultimately resulting in a decrease in diurnal mean StWC and an increase in the diurnal range of StWC.

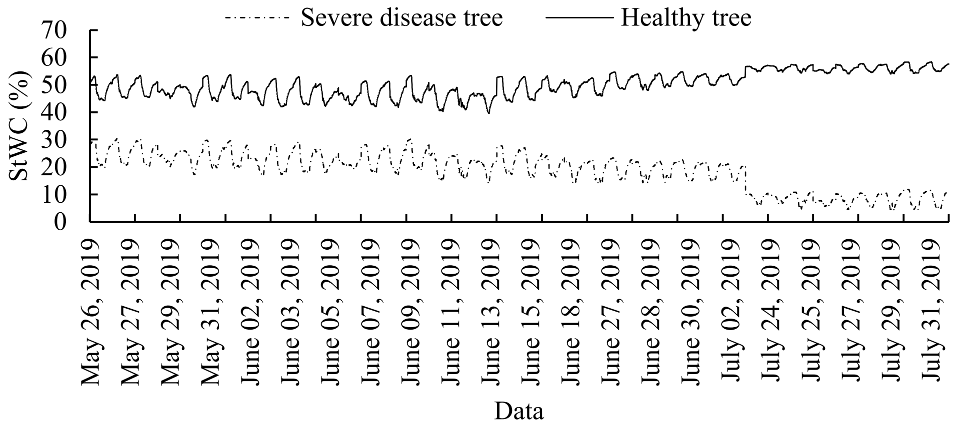

Figure 4. Changing curves of StWC in *Lagerstroemia indica* L. with different health levels during the period of germination.

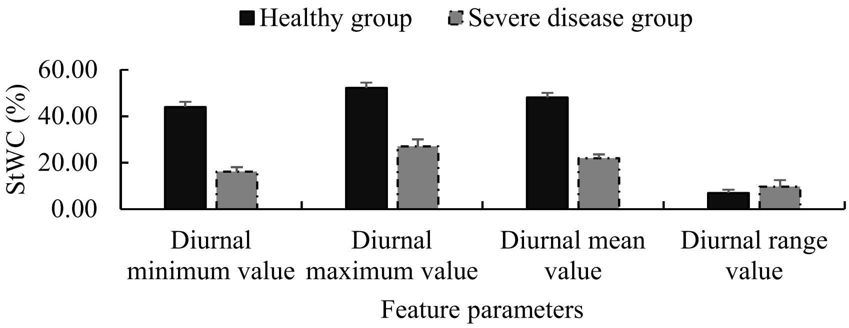

Figure 5. The means and standard deviations of four feature parameters of StWC measured on June 1 among different groups of *Lagerstroemia indica* L.

Table 5. One-way analysis of variance to examine the effects of disease on four feature parameters of StWC in *Lagerstroemia indica* L.

Feature Parameters	Source	Sum of Squares	*df*	Mean Square	*F*	*p*
Diurnal minimum StWC	Between groups	0.953	2	0.476	421.562	<0.001
	Within groups	0.078	69	0.001		
Diurnal maximum StWC	Between groups	0.778	2	0.389	368.243	<0.001
	Within groups	0.073	69	0.001		
Diurnal mean StWC	Between groups	0.842	2	0.421	534.468	<0.001
	Within groups	0.054	69	0.001		
Diurnal range of StWC	Between groups	0.009	2	0.004	10.350	<0.001
	Within groups	0.029	69	<0.001		

Degree of freedom (*df*), F-Value (F), *p*-Value (*p*).

3.4. Comparison of Stem Water Content of Naturally Grown *Pinus sylvestris* var. *mongholica* Litv.

Figure 6a shows the StWC values measured in one day in the first group of *Pinus sylvestris* var. *mongholica* Litv., whereas Figure 6b shows the diurnal range of StWC in the same group. The diurnal range of StWC of trees with emergence holes is larger than that of those with no emergence holes. The presence of emergence holes on the trees suggests that the trees are damaged by pests and have low vitality. Therefore, the results indicate that the diurnal range of StWC increases with decreasing plant vitality. Figure 7a depicts the StWC values measured under four health conditions in the second group of *Pinus sylvestris* var. *mongholica* Litv.; the diurnal range of StWC is shown in Figure 7b. The diurnal range of StWC of healthy trees was the lowest; the diurnal range of StWC increased gradually with decreasing plant vitality. In leafless *Pinus sylvestris* var. *mongholica* Litv. Trees, the diurnal range of StWC was the highest, which also indicates that StWC is closely related to plant vitality. The results of the first and second experiments suggest that StWC can be used to evaluate plant vitality, and the diurnal range of StWC can effectively reflect the changes in plant vitality.

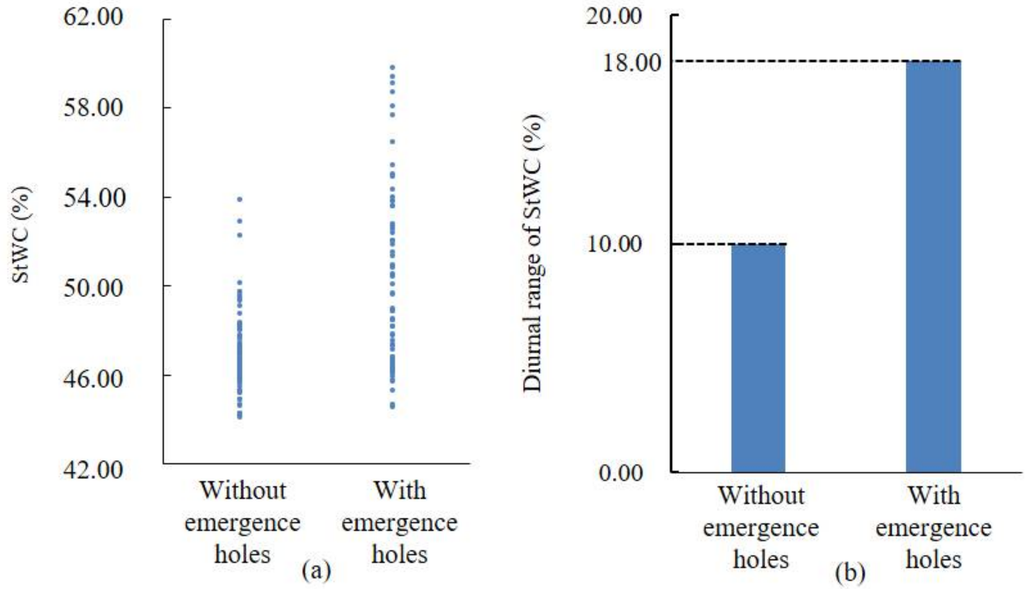

Figure 6. The first experimental group of *Pinus sylvestris* var. *mongholica* Litv. (**a**) StWC of trees without and with emergence holes. (**b**) Diurnal range of StWC.

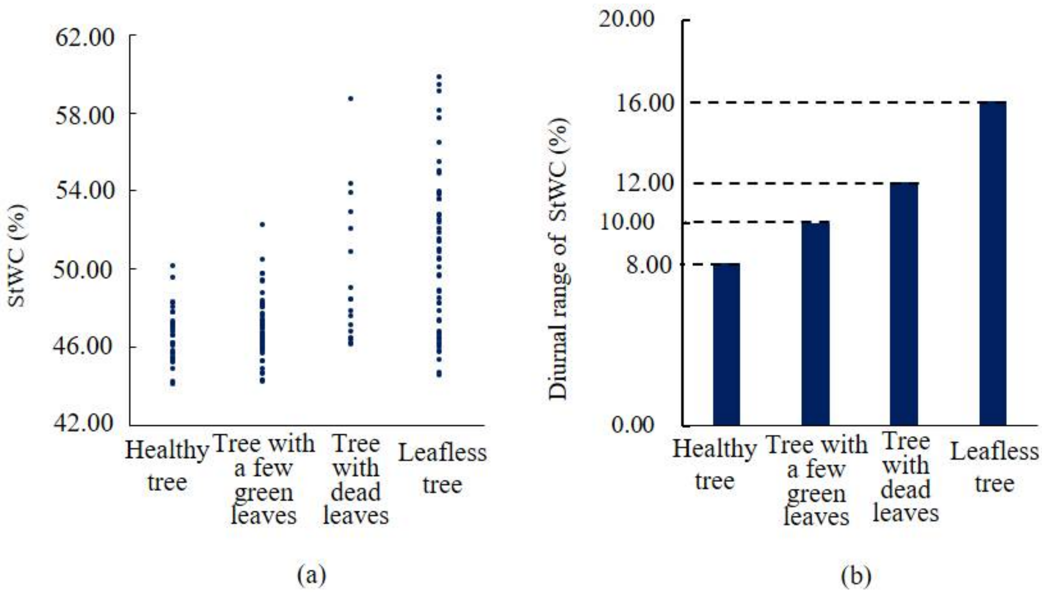

Figure 7. The second experimental group of *Pinus sylvestris* var. *mongholica* Litv. (**a**) StWC of trees in four different health conditions. (**b**) Diurnal range of StWC for trees in four different health conditions.

3.5. Comparison of StWC Changes in Malus micromalus Makino under Drought Stress

Figure 8a shows the StWC changes in *Malus micromalus* Makino under normal irrigation and drought stress. *Malus micromalus* Makino under normal irrigation and without irrigation consistently showed stable fluctuations in stem water until 15 June 2019, and the StWC of *Malus micromalus* Makino without irrigation began to fluctuate and decline after 15 June. Further analysis of the diurnal range and diurnal mean of StWC showed that the diurnal range of StWC for *Malus micromalus* Makino under normal irrigation was less than 4% in Figure 8b, However, from 15 June, the diurnal range of StWC for *Malus micromalus* Makino without irrigation showed a trend of slowly fluctuating and becoming larger, and it reached about 10% on 20 June, and thereafter the diurnal range of StWC fluctuated significantly around 10%.The diurnal mean of StWC for *Malus micromalus* Makino under normal irrigation fluctuated very little and was basically around 47% in Figure 8c, the diurnal mean of StWC for *Malus micromalus* Makino without irrigation also was basically around 47% until 15 June, after which it started to decline to about 42% and remained stable again from 20 June, and then from 20 June started to drop again consistently.

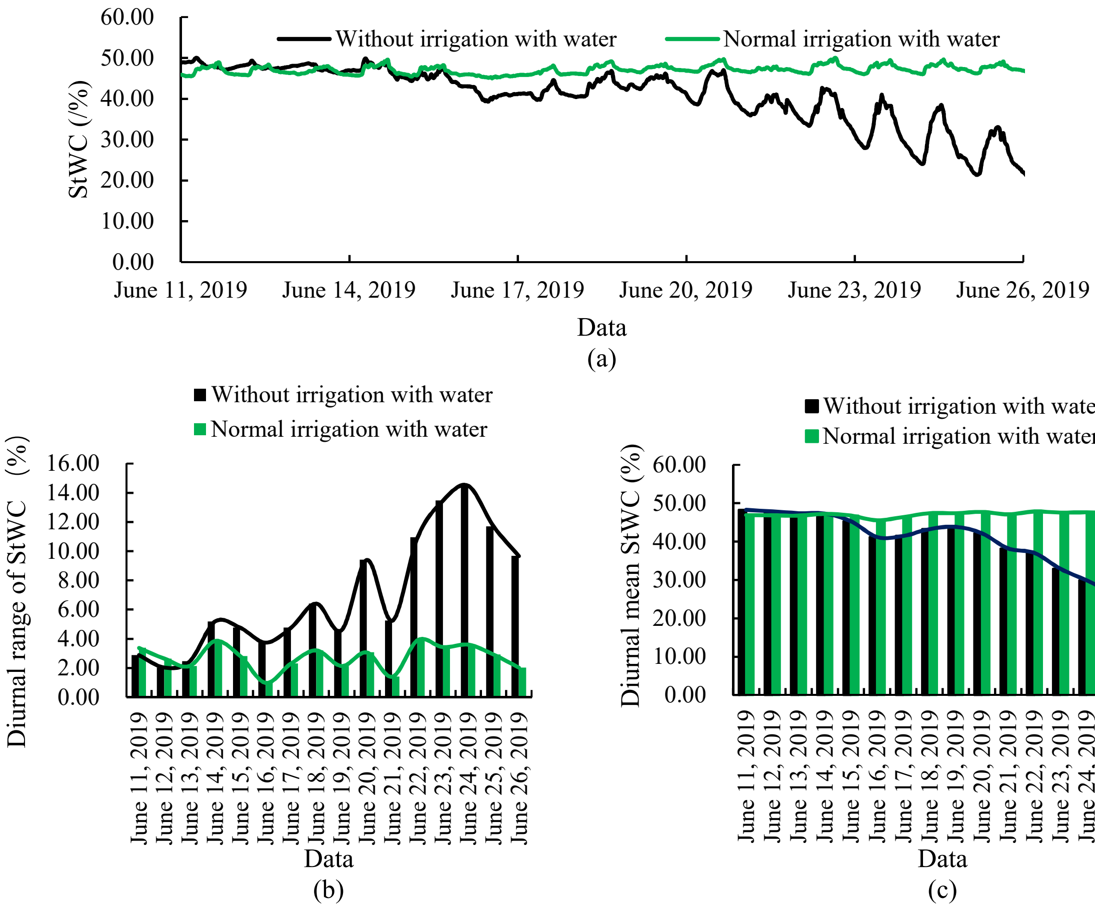

Figure 8. StWC changes in normal irrigation with water and without irrigation with water: (**a**) StWC of *Malus micromalus* Makino. (**b**) Diurnal range of StWC for *Malus micromalus* Makino. (**c**) Diurnal mean of StWC for *Malus micromalus* Makino.

3.6. StWC Changes in Pinus tabuliformis Carriere during the Overwintering Period When Experiencing Freeze-Thaw Stress

Figure 9 shows changes in StWC of *Pinus tabuliformis* Carriere before and after entering the overwintering period. Before the overwintering period, the ambient temperature was above 0 °C and the StWC fluctuated steadily at about 27%. The vitality of *Pinus tabuliformis* Carriere declines when StWC begins to decline rapidly until the plant goes dormant for overwintering, at which point stem moisture remains at a low level of about 10%.

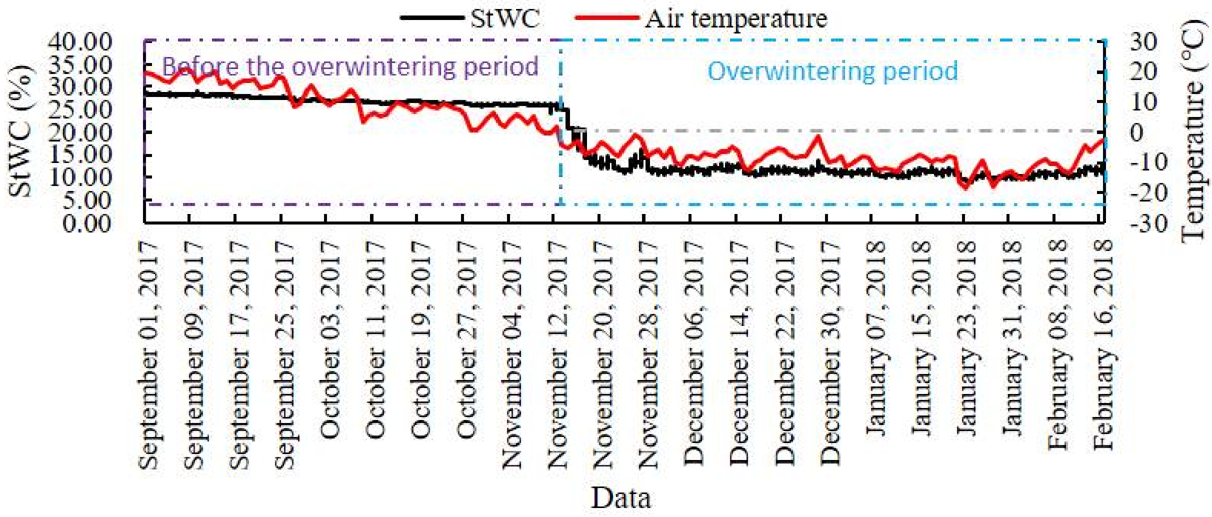

Figure 9. StWC changes in *Pinus tabuliformis* Carriere during the overwintering period when experiencing freeze-thaw stress.

4. Discussion

4.1. Significance of Measuring Stem Water Content

The water storage capacity of stems determines the tree phenology and distribution [25], and StWC can be used as an indicator of plant water stress [26]. The saturated stem water content is inversely proportional to wood density; thus, dynamic changes in wood density during plant growth can be evaluated by measuring StWC [27]. Stem water content is easy to measure in the field. Stem embolisms affect the flow of sap and the proportion of water in the stem; therefore, StWC can be used to detect the presence of embolisms in tree stems [28]. In addition, biological and abiotic stresses usually affect StWC, then StWC can be used to evaluate the stress degree and provide technical support for the study of plant stress resistance. Moreover, irrigation strategies based on plant physiological parameters such as StWC have received increasing attention in research aiming to improve the efficiency of plant irrigation and save water resources [29–31]. Therefore, measuring StWC is of great significance.

4.2. Correlation between Stem Water Content and Plant Physiological Parameters

Figure 3 shows that Pn, Tr, and Gs were significantly negatively correlated with StWC, and Ci was significantly positively correlated with StWC. The correlation between StWC and physiological parameters can be clearly explained in terms of plant physiology. This shows that Pn accelerates with the increase in light intensity in the morning, and the rapid production of organic matter in plants increases the demand for water and carbon dioxide, reducing Ci, The increase in Gs leads to an increase in Tr, improving the water transport efficiency [21,22], the stem tissue transports part of the water to the leaves through ducts, which leads to a decrease in StWC. However, the plants take a short siesta at noon; Pn, Tr, and Gs decrease; Ci increases; leaf water demand decreases; and StWC increases slightly. The close correlation between StWC and plant physiological parameters (Pn, Tr, Gs, and Ci) indicates that StWC can effectively reflect information on the vital activity status of plants [32,33].

4.3. Distribution and Transportation of Water in the Stem

The dynamic change in StWC is mainly attributed to the distribution and transportation of water in the stem. Therefore, StWC can reflect the distribution and transportation of water in the stem to a certain degree. Nakada et al. suggest that sapwood contains a large amount of water distributed evenly, whereas heartwood contains a smaller amount of water distributed unevenly [34], and water transport occurs primarily through the vessels and tracheids of the xylem in the sapwood and heartwood [35]. Therefore, water is mainly concentrated in the vessels and tracheids of the sapwood, which is chiefly responsible for the transportation of water and minerals in plants and has a certain water storage capacity [36], and changes in the distribution and transport of water in the sapwood are accompanied by changes in StWC; the good distribution and transport of water in the stem is the basis for healthy plant growth, which proves that it is feasible to assess plant vitality by StWC.

4.4. Stem Water Imbalance under Decreased Plant Vitality Conditions

The decrease in StWC and the increase in StWC fluctuations (Figures 4, 6 and 7) indicate that the distribution and transport of water in the stem is disrupted and the stem's ability to store and transport water is reduced [37], at a time when we know that the tree is suffering from pest and disease infestation. Under conditions such as plant senescence and pest and disease infestation, plant vigor decreases and normal metabolism is disturbed. A series of changes and disruptions in physiological functions and structural tissues occur, usually manifested by symptoms such as discoloration and wilting of leaves, and the tilting and embolism of stems and branches [38–40]. This conclusion is consistent with our finding that compared to unhealthy tress, healthy trees have better water regulation which leads to a smaller diurnal range of StWC. Therefore, StWC can be used to determine whether plants suffer from pests and diseases and further assess their vitality, which may have important practical implications for plant pest and disease control.

4.5. Self-Adjustment of Plants to Adapt to Stressful Environments When Vitality Decreases

The StWC of *Malus micromalus* Makino under normal irrigation and without irrigation in Figure 8 showed significant variability, indicating that StWC can effectively characterize abnormalities in plant vital status, and the fluctuation of StWC in the form of diurnal variation also proves that the tree stem has the function of water storage and self-regulation [11,41,42]. The diurnal range and diurnal mean of StWC for *Malus micromalus* Makino under normal irrigation and without irrigation which indicate that the plant is in dynamic equilibrium in a healthy state and will self-regulate to maintain its dynamic stability [43,44]. Moreover, plant in a healthy state also have certain resistance to stress. The diurnal range of StWC for *Malus micromalus* Makino under normal irrigation and without irrigation before 15 June in Figure 8b were within 4%, and the diurnal mean of StWC fluctuated around 47% (Figure 8c), respectively, which clearly support this conclusion. When the stress suffered by the plant persisted with entering into a sub-healthy state, and in order to resist this sub-healthy state, the plant gradually slowed down and shut down the related vital activities and reduced water consumption, it also still had some regulation ability to itself, so the diurnal range and diurnal mean of StWC in Figure 8b,c showed a trend of slow fluctuation after 15 June. As drought stress continues, the water deficit in the plant will lead to the death of a large number of cells in the plant, at which point the plant becomes less vigorous and begins to lose its ability to regulate itself [45]; the irreversible decline of stem moisture at 20 June in Figure 8 also proves the point of attention that the plant is in an irreversible dying state at this time. To ensure the health of the plant, irrigation should be started as soon as the diurnal range and diurnal mean of StWC fluctuate more than normal. Hence, StWC can be used to set irrigation thresholds and provide technical support for precision water-saving irrigation.

Constantz et al. pointed out in a previous report that plants are subjected to freeze–thaw stress at low temperatures during the overwintering period, and vitality vigor decreases significantly to reduce unnecessary consumption. In order to successfully pass through the overwintering period, plants need to go through the cold training process first and through a transitional stage is itself gradually adapted to deep winter [46–49], and the fluctuating decline process of StWC in the pre-wintering period in Figure 9 indicates the occurrence of this feature, confirming that cold domestication The process of cold domestication and warm domestication may have important physiological significance. At the same time, the higher the water content in plants during the overwintering period, the more likely the plant tissues will freeze, and the ice crystals generated in the cells will lead to cell death more easily [50–53]; this is also evidenced by the fact that the StWC of *Pinus tabuliformis* Carriere was maintained at about 10% during the late overwintering period in Figure 9, Plants make it more difficult for themselves to produce large amounts of ice crystals by keeping the water content low.

4.6. Advantanges of Stem Water Content Based on EWIFI Sensor

There are many studies on water detection based on the dielectric principle [54–56], but the instrumentation is expensive [56] and invasive [47,54]. The EWIFI sensor uses a ring probe, which can measure StWC nondestructively. Based on Figure 3, it can be seen that each parameter or StWC may have a similar effect in assessing plant vitality, but the sensor has a low cost and a small size, and it is easy to be widely used in the field; it can monitor the tree stem water change in real time and online for a long time, which will greatly reduce the workload of acquiring plant physiological parameters. StWC is closely related to plant physiological parameters and plant health status, thus providing a new and easily accessible parameter for assessment of plant vitality, including drought resistance, cold resistance, and disease resistance. In the next step, we will further improve the EWIFI sensor so that it can be installed separately and used in large quantities, and StWC can be monitored nondestructively, in real time, remotely and extensively by the EWIFI sensor.

5. Conclusions

In the present study, the change in StWC under decreased plant vitality was studied using the novel EWIFI sensor, and the feasibility of the sensor was analyzed. The results suggest that StWC can be used to characterize plant vitality to a certain extent, by comparing the correlation between stem water content and plant physiological parameters and changes in stem water content with plant vitality. The EWIFI sensor can be used to estimate StWC, and it has the advantages of low cost, convenient and non-destructive measuring. StWC, as a new plant physiological parameter, can be used to assess plant vitality. It is also possible to combine the EWIFI sensor with the smart internet of things and artificial intelligence algorithms [57–60] to study soil water and plant water prediction problems at different time scales [61–63], which can be applied to other engineering systems in combination with environmental parameters [64–66].

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