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Towards Continuous Stem Water Content and Sap Flux Density Monitoring: IoT-Based Solution for Detecting Changes in Stem Water Dynamics

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Abstract: Taking advantage of novel IoT technologies, a new multifunctional device, the "TreeTalker", was developed to monitor real-time ecophysical and biological parameters of individual trees, as well as climatic variables related to their surrounding environment, principally, air temperature and air relative humidity. Here, IoT applied to plant ecophysiology and hydrology aims to unravel the vulnerability of trees to climatic stress via a single tree assessment at costs that enable massive deployment. We present the performance of the TreeTalker to elucidate the functional relation between the stem water content in trees and respective internal/external (stem hydraulic activity/abiotic) drivers. Continuous stem water content records are provided by an in-house-designed capacitance sensor, hosted in the reference probe of the TreeTalker sap flow measuring system, based on the transient thermal dissipation (TTD) method. In order to demonstrate the capability of the TreeTalker, a three-phase experimental process was performed including (1) sensor sensitivity analysis, (2) sensor calibration, and (3) long-term field data monitoring. A negative linear correlation was demonstrated under temperature sensitivity analysis, and for calibration, multiple linear regression was applied on harvested field samples, explaining the relationship between the sample volumetric water content and the sensor output signal. Furthermore, in a field scenario, TreeTalkers were mounted on adult *Fagus sylvatica* L. and *Quercus petraea* L. trees, from June 2020 to October 2021, in a beech-dominated forest near Marburg, Germany, where they continuously monitored sap flux density and stem volumetric water content (stem VWC). The results show that the range of stem VWC registered is highly influenced by the seasonal variability of climatic conditions. Depending on tree characteristics, edaphic and microclimatic conditions, variations in stem VWC and reactions to atmospheric events occurred. Low sapwood water storage occurs in response to drought, which illustrates the high dependency of trees on stem VWC under water stress. Consistent daily variations in stem VWC were also clearly detectable. Stem VWC constitutes a significant portion of daily transpiration (using TreeTalkers, up to 4% for the beech forest in our experimental site). The diurnal–nocturnal pattern of stem VWC and sap flow revealed an inverse relationship. Such a finding, still under investigation, may be explained by the importance of water recharge during the night, likely due to sapwood volume changes and lateral water distribution rather than by a vertical flow rate. Overall, TreeTalker demonstrated the potential of autonomous devices for monitoring sap density and relative stem VWC in the field of plant ecophysiology and hydrology.

Keywords: IoT; TreeTalker; sap flux; stem water content; transient thermal dissipation; capacitance sensor

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1. Introduction

Severe water stress can result in both hydraulic failure and carbon starvation, contributing to the greater phenomena of tree mortality [1]. Tree physiological parameters such as sap flow and stem water content perform as plant-based water stress indicators [2,3]. The variation in the sap flow and stem water content of a tree plays a biologically significant role in tree status and function, with respect to internal and external drivers such as anatomical wood anatomy and vapor pressure deficit [4]. Under water deficit, stem water storage contributes to transpiration, thus helping to achieve a balance between root water uptake and water transpiration [5–11]. The variation of stem water content in trees may depend on multiple factors such as species, growth form, size, competition, phenology, and abiotic environmental conditions [12–14]. Several studies have reported on the diurnal, nocturnal, seasonal, and annual dynamics, and ranges of stem water content, by applying different methods to living trees [8,12,15,16].

To measure stem water content, many direct and indirect approaches were developed including the oven-drying method [17], gamma-ray attenuation [18], nuclear magnetic resonance [19,20], electrical conductivity, and time-domain reflectometry (TDR) [11,21–24], as well as using heat as a tracer in the tangential direction of the stem [12,25,26].

However, many of the available techniques to measure stem water content exhibit limitations and specific drawbacks, as addressed appropriately by [9,24,27]. For instance, the kiln-dry or oven-drying method [17] delivers precise results which are used to calibrate measurement equipment. However, the sampling methods necessitate the destructive extraction of a physical wood specimen, and furthermore, its application is time-consuming [27]. Indirect approaches such as the TDR probe and the microwave method in turn, although non-invasive and very accurate, are quite expensive for continuous monitoring [15,16,22–24,28,29].

Thermal approaches are another category for determining both sap flux density (SFD) and the stem water content in living trees [25,30]. A non-empirical heat-pulse-based method, Sapflow+ [25], was developed to measure temperature changes around a linear heater in both axial and tangential directions, after the application of a heat pulse from a sensor within the stem. However, despite this being a method for continuous stem moisture monitoring, it only provides stem moisture in zero flux conditions (i.e., usually during the nighttime) [26]. In general, there is an increasing interest in having continuous parallel measurements of sap flow and stem moisture, since the latter is a fundamental parameter to correctly detect the thermal equilibrium point or zero-flux conditions [26,31].

Capacitive sensing by rapidly charging and discharging a positive ground electrode (capacitor) has gained increasing importance in the last decades in the industrial and automotive sectors. Its application to detect moisture content in materials (i.e., wood) and soils has been proven to be effective [24,32–36]; however, its application to tree physiology is still under exploration [16,24,37–43] and there are limited articles available on simultaneous stem water detection with sap flow monitoring at the same timescale [12,25,44,45].

To address these issues, we have developed a new capacitive sensor to continuously monitor stem water content in parallel with SFD measurements, in order to provide long-term measurements across daily and seasonal timescales. Therefore, the objectives of this investigation are (1) the design, validation, and application of a new capacitive sensor toward stem water content measurement, (2) sensor sensitivity analysis under controlled conditions to detect temperature and different matrix impacts on the sensor signal output (3), to capture and assess changes in daily and seasonal stem water content, and (4) to demonstrate a novel IoT low-cost mass monitoring application for forests. In addition, the sensor is connected to an IoT platform [46–48], which transmits data in real-time to the cloud and from the cloud to the desktop. The main aim of the paper is to present a novel capacitance probe for continuous stem water monitoring and to integrate such capability into a sap flow monitoring device already developed by our group.

The study is based on a combination of two separate but related experiments. Firstly, we analyze the experimental results on the temperature sensitivity of the sensor and the related species-specific stem moisture calibration responses. Secondly, the sensors were integrated with the TreeTalker platform and installed on trees in the field to monitor both sap flow and stem water content dynamics under field conditions.

2. Material and Methods

2.1. The TreeTalker Platform

The present study is based on the integration of a new capacitance probe for stem water detection into the existing TreeTalker platform (TT+) for tree physiology research. The TreeTalker is an IoT platform which is able to measure tree physiology parameters such as sap flow, canopy-transmitted light spectra (12 bands), stem growth, tree stability (via an accelerometer sensor), and basic climate parameters (air temperature and humidity) [46–48]. However, the focus of this study is on exploring the water-related indicators (sap flux density and stem water content) in forests, using a combination of the TreeTalker's heater and reference probes.

The TT+ sap flow measurement technique is based on the temperature difference between a pair of probes, the reference (Ref) probe and the Heater probe, which are inserted radially in the tree trunk with a vertical separation of 10 cm, facing north, and covered by a reflective shield to avoid direct solar heating, which may impact the registered temperatures [49]. One of the probes is heated, while the other is used to measure the stem temperature and stem water content using a thermistor and a capacitance sensor with the frequency band of 50 KHz, respectively (Figure 1). TT+ sap flow measurement is designed based on the transient thermal dissipation (TTD) technique with a cyclic heating system (by default: 10 min of heating/50 min of cooling) to measure the sap flow [50–54]. The transient signal (dT) is the relative change in temperature over the heating period, calculated as the temperature difference between the probes reached at the end of the heating phase (ΔT_{on}) and just before the heating phase (ΔT_{off}) [53]:

$$dT\ (^{\circ}C) = \Delta T_{on} - \Delta T_{off} \quad (1)$$

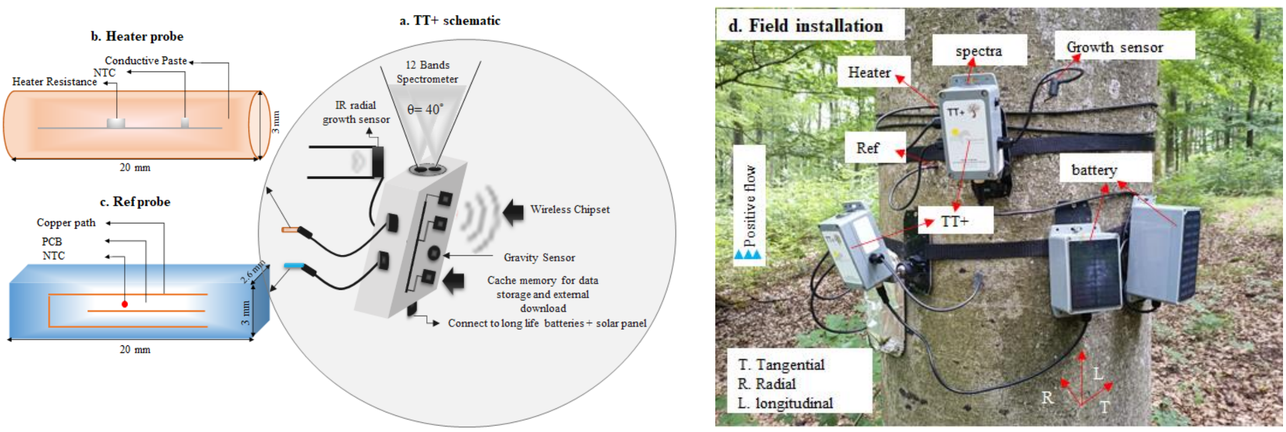

Figure 1. (**a**) TT+ layout, (**b**) Heater probe including a thermistor (NTC) and a heater resistance, which are placed in a conductive paste, (**c**) Ref probe including a thermistor (NTC) and a copper path as a capacitance oscillator, and (**d**) installation of two TreeTalkers (TT+) on a beech tree.

The transient signal is normalized by its value at zero flow to estimate a transient index K:

$$K = \frac{dT_0}{dT_u} - 1 \quad (2)$$

where dT_0 is the maximum transient signal obtained under zero flow conditions and dT_u is the measured signal at a given *SFD*.

To estimate the *SFD* ($l\ dm^{-2}\ h^{-1}$), a non-species-specific calibration equation is conducted by utilizing the transient index (K) [54].

$$SFD\left(l\ dm^{-2}\ h^{-1}\right) = \left(11.3 \times \frac{K}{1-K}\right)^{0.707} \tag{3}$$

2.2. Sensor Design for Stem Water Content Monitoring

The principal idea was to modify the Ref temperature probe of a classic sap flow sensing device, as in the TreeTalker system, to include a new capacitance sensor for sensing wood water content.

A capacitance sensor can capture the change in the electric capacitance of stems exposed to an electromagnetic field, by detecting the change in the dielectric properties. This method delivers an acceptable accuracy for wood moisture contents from 2% up to fiber saturation point [27], whereas it may lead to incorrect records for values above the saturation point. At a low frequency of the generated electromagnetic field, the value may be incorrect, owing to short circuit currents in the wood [35]. Material density, material temperature, and voltage frequency are the main influences on the measurements [55]. The development of capacitance sensors may offer flexibility and efficiency regarding indirect stem water content measurement.

In this study, the Ref probe has been realized with a copper PCB design with two traces forming the electrodes (one grounded and one signal), which are separated by 1.5 mm. The sensor has a rectangular cross-section and therefore implanting it inside the stem wood requires a properly engraved 2 mm deep cut (Figure 2).

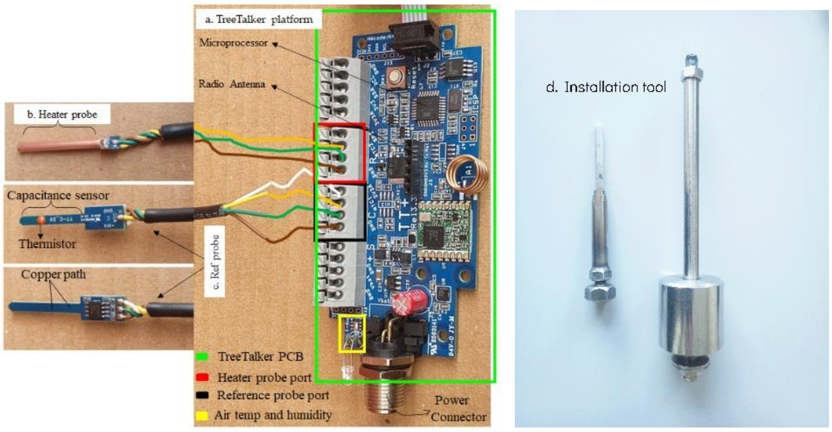

Figure 2. (**a**) TreeTalker platform based on ATMEGA 328 P 8-bit processor AVR RISC 8 MHz, (**b**) Heater probe, 0.2 watts, (**c**) Ref probes including a capacitance sensor and a thermistor, front and back, respectively, and (**d**) installation tool for the Ref probe.

Usually, the capacitance probe is inserted in an *RC* circuit (Figure 3) which is a low pass filter whose cutoff frequency ECf_c (Hz) is defined as:

$$ECf_c = \frac{1}{2}\pi\ R\ C, \mathrm{R} = \text{resistance}\ (\Omega), \mathrm{C} = \text{capacitance}\ (\mathrm{F}) \tag{4}$$

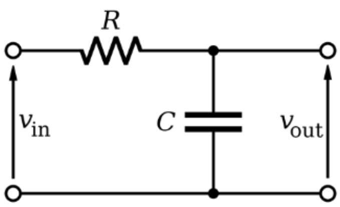

Figure 3. RC filter circuit.

At the cutoff frequency, the input signal (V_{in}) is attenuated by 70.7%. In general, the output signal amplitude (V_{out}) is attenuated in the function of frequency (ECf) as follows:

$$V_{out} = V_{in} \frac{1}{ECf\ R\ C + 1} \tag{5}$$

This setting is applied in most of the available commercial sensors for soil moisture sensing [28,55–57] where a fixed frequency is applied (usually >1 MHz). We have, however, used a different approach where the capacitance of the moist wood is integrated with an astable oscillator and the output frequency is variable in relation to the change in capacitance (see Figure 4, where C is the wood moisture wood capacitance).

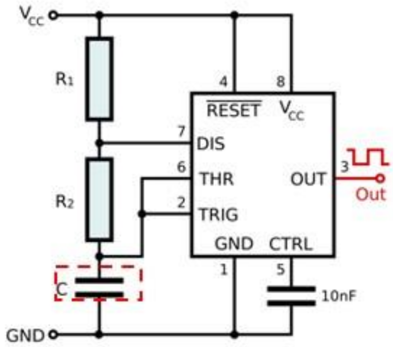

Figure 4. TreeTalker oscillator circuit using 555 Timer.

In this case, the variable frequency output (ECf) is given by:

$$ECf = \frac{1.44}{(R_1 + 2R_2)C} \tag{6}$$

In the first case, the main parameter is voltage sensing, which is acquired as an analog signal. In the second approach, the main output is an oscillating signal (square wave) whose frequency is measured by the time counter digital pin of the TreeTalker microprocessor. For the sake of simplicity, throughout the paper, we report the frequency data as the parameter related to the capacitance changes. For this reason, calibration is also performed between the stem moisture data and frequency. The advantage of the proposed new scheme is that the sensitivity of changes in frequency in relation to capacitance is higher in the frequency domain than in the voltage domain.

2.3. Lab Experiments

2.3.1. Temperature Dependence of Ref Probe

Dielectric moisture sensors are known to respond to temperature variations [58,59]; therefore, a temperature sensitivity analysis was conducted under controlled conditions using a climatic chamber with a selected temperature range from 5 to 35 °C, with temperature steps of 5 °C/30 min, to detect the temperature influence on the probes' frequency output when the signal is stabilized. For the temperature sensitivity tests, the capacitance probe was placed in different substrates: distilled water, water-saturated pine sawdust (commercial sawdust: a mixture of *Picea abies* L.and *Abies alba* Mill.), and fresh-cut wood samples of *Fagus sylvatica* L., *Populus nigra* L., and *Pinus sylvestris* L. For each substrate, three temperature repetitions were conducted, respectively, where wood moisture content was assumed to be constant during each repetition since the samples were sealed with parafilm.

2.3.2. Species-Specific Calibration

Fresh-cut wood samples from different species were collected from the Marburg Open Forest of the Philipps-Universität Marburg [60] to conduct the species-specific calibration for the recorded frequency data (ECf (Hz)) by the Ref probe, in comparison with the oven-drying method [17], as a reference technique of measuring wood water content. The species-specific calibration was conducted on *Fagus sylvatica* L. (beech), *Quercus petraea* L. (oak), and pine sawdust with different densities of 0.52, 0.53, and 0.18 g/cm^3, correspondingly. Wood samples of beech and oak were harvested from the same trees at DBH in different directions, north (beech-1), south (beech-2), and for the oak, north (oak-1) and east (oak-2), respectively (Figure 5).

Figure 5. (**a**) Installation of Ref probe at DBH, 10 days before harvesting wood samples, (**b**) harvesting beech and oak trees to collect fresh-cut wood samples including Ref probes, and (**c**) using harvested samples to conduct the species-specific calibration for Ref probe TT+.

Previous studies have reported wound impacts on measurements from sensors measuring sap flow and stem water content [61]. Damaged vascular tissue response to probe insertion presents a problem that can last a few hours to a few days, dependent on wound occlusion, and as such, impacts sensor signal normalization in both lab and field experiments. To avoid air gap and wound impact on the data, Ref probes were installed in living trees on 21 October 2020 and harvested on 2 November 2020 to establish the passage of wound occlusion (Figure 5). The harvested samples were analyzed in the lab, where, using a TT+ connected to the Ref probe, continuous temperature and frequency (ECf (Hz)) data were recorded. In parallel, sample weight loss was recorded by a digital balance for each sample, as a standard technique to determine volumetric water content. Sample data were continuously collected via the balances and TT+ until the specimen mass stabilized at the approximate constant value. Each sample, with and without a Ref probe, was weighed at the end of the drying procedure in the laboratory. The differences considered, i.e., those pertaining to with/without a Ref, equate to the net mass of the sample during the experiment. Subsequently, dry mass was determined after the wood samples were oven-dried for 48 h at 75 °C. Such a temperature is considered to be sufficient to allow complete water evaporation and at the same time avoid significant destruction of the wood structure [17]. Ultimately, the gravimetric water content (θ_g) and volumetric water content (*stem VWC*) were calculated using the following equations:

$$\theta_g \left(g\, g^{-1}\right) = \frac{W_f - W_{oven-dry}}{W_{oven-dry}} \tag{7}$$

$$stem\ VWC\ (\%) = \theta_g \times \frac{\rho_{wood}}{\rho_{sap}} \times 100 \tag{8}$$

where the W_f is the fresh weight of the sample (g), W_{oven_dry} is the oven-dry weight (g), the term ρ_{wood} is the basic density of the wood sample ($\frac{g}{cm^3}$) and ρ_{sap} is the sap density ($\frac{g}{cm^3}$), assuming its equality to the water density. In fact, the density of water is close to 1 and is often ignored [62]. ρ_{wood} is the ratio of wood oven-dry mass to sample fresh volume. Fresh volume was calculated by carefully measuring the dimensions of the samples with digital calipers with an accuracy of 0.01 mm.

2.4. Study Site and Field Experiments

To assess the TreeTalker (TT+) capability under field conditions, a managed beech-dominated forest in the lower mountain ranges of Western Germany near Caldern (8°40′ E; 50°50′ N) was chosen. The forest is owned by Philipps-Universität Marburg and is an experimental site for the biodiversity monitoring project, Nature 4.0 [60], and is characterized by a forest covering an area of 1.5 km^2, dominated by *Fagus sylvatica* L. and *Quercus petraea* L. (Mattuschka) Liebl of different age classes. The elevation level ranges from 260 to 410 m a.s.l. The predominant soil type is Cambisol. Historical data on air temperature, humidity, and precipitation are measured via the MOF climate station. Using air temperature and humidity data, the vapor pressure deficit (VPD) was analyzed for 2020 and plotted vs. precipitation in Figure 6. The average annual air temperature and precipitation for 2020 in the selected site were reported at 9.7 °C and 374 mm, respectively. As reported in the previous study about the European heatwave's impact on Western Germany [63], correspondingly, in this site, from 15 July to 15 August, we showed an increasing trend in the VPD up to a maximum of 3.8 KPa, due to high temperatures and few rainfall events (Figure 6). The maximum recorded rain event was 21.2 mm, which occurred on 17 June. Here, in spring 2020, TT+, n = 59, were mounted at 1.30 m or diameter at breast height (DBH) to monitor the dynamics of SFD and stem water content (Figure 7). In particular, TT+ demonstrates the applicability and functionality of the Ref probe in distinguishing plant hydraulic functionality under different meteorological circumstances.

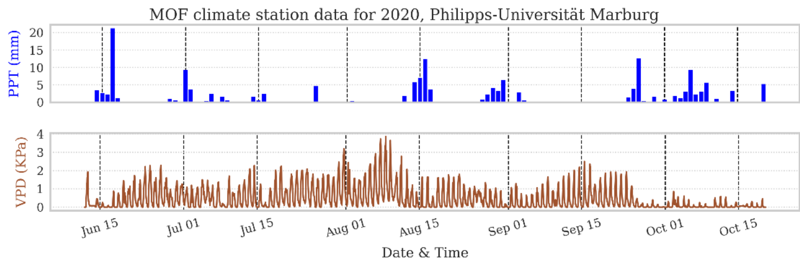

Figure 6. Precipitation (PPT (mm)) and vapor pressure deficit (VPD (kPa)) for 2020, based on data from the climate station in the Marburg Open Forest (MOF) study area.

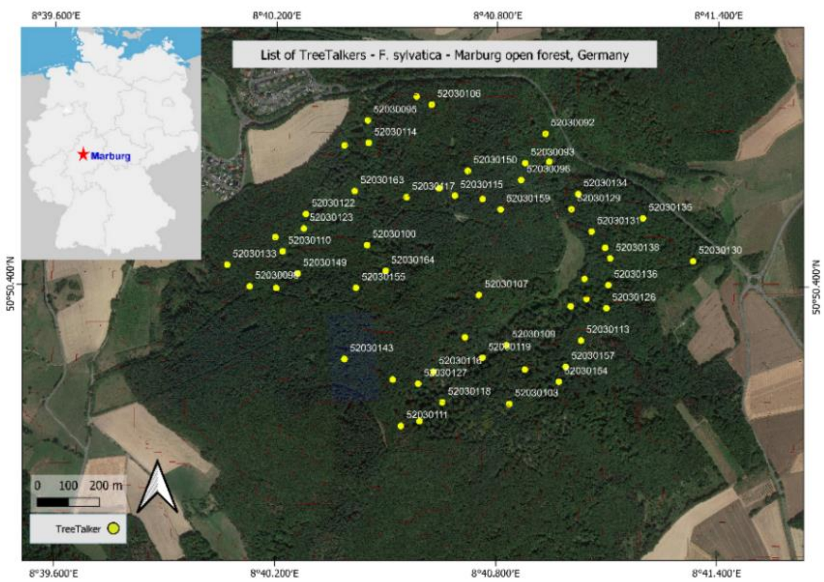

Figure 7. Map of the study area, Marburg Open Forest (MOF), showing the location of the mounted TreeTalkers on beech trees.

Table 1 displays the ancillary variables associated with the selected trees to discuss the diurnal fluctuation of water-related indicators for the MOF area.

Table 1. Height, diameter at breast height (DBH), sapwood area, and canopy volume for the selected trees for individual responses.

TT+ No.	Height (m)	DBH (cm)	Sapwood Area (cm^2)	Canopy Volume (m^3)
TT25	29.9	53	685	879
TT54	32.7	56	806	1017
TT62	29.5	53	615	1801

3. Results and Discussion

3.1. Lab Experiments

3.1.1. Temperature Sensitivity Analysis of Ref Probe

The temperature sensitivity analysis results show a negative correlation between capacitance sensor data (ECf (Hz)) and wood sample temperature (T (°C)) (Figure 8). The relationship between ECf (Hz) and T (°C) is assessed by a linear regression model (y = m_1x + b_1), assuming a constant moisture content during the experiment (Figure 8). The coefficients 'm_1', the slope of the linear model, and 'b_1', the intercept, are presented in Table 2 for each substrate.

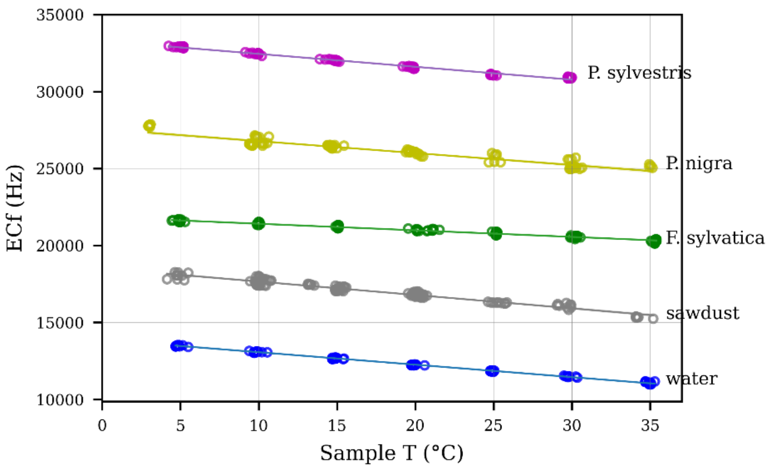

Figure 8. Temperature sensitivity analysis for the capacitance sensor used in the Ref probe TT+ across different substrates.

Table 2. Temperature sensitivity analysis for TreeTalker's Ref probe exposed to different substrates. Coefficients 'm_1 ' and ' b_1 ' are presented for a linear equation in the standard form of $ECf_T = m_1 * T + b_1$.

Var	Water	Sawdust	*F. sylvatica*	*P. nigra*	*P. sylvestris*
Slope (m_1)	−81	−87	−43	−84	−78
Intercept (b_1)	13,867	18,519	21,834	33,283	27,555
R^2	0.98	0.88	0.94	0.98	0.81
p-value	<0.01	<0.01	<0.01	<0.01	<0.01
stderr	0.53	0.92	0.45	0.41	1.28

Our empirical findings show that not only temperature affects the performance of the Ref probe, but also matrix types and their physical properties. Although the results are clearly displaying a negative linear relationship between material temperature and ECf, the slope of the linear regression model, m_1, across the various substrates, is neither constant nor similar. This demonstrates that textural features of our samples have a remarkable impact on frequency data recorded by the Ref probe (Figure 8).

3.1.2. Species-Specific Calibration

The calibration equations for the two wood types (beech and oak) and the pine sawdust sample (Figure 9) were determined using multiple linear regression models, considering the impacts of frequency records (*ECf* (Hz)) and stem temperature (*T* °C). The multiple linear regression model takes the volumetric water content of samples using the reference gravimetric data as one parametric component, with stem temperature *T* and ECf as the Ref probe's output. The below equation can be used to determine the stem volumetric water content (*stem VWC*) in a percentage using the Ref probe's raw records in living trees.

$$stem\ VWC\ \%^{Matrix}_{(T,\ ECf)} = \beta_0 + \beta_1 \times T + \beta_2 \times ECf + \epsilon \tag{9}$$

where β_0 is the intercept, and β_1 and β_2 are the slope coefficients of the *T* and *ECf* records, respectively. ϵ is the model's error term (see Table 3). The multivariate analyses for beech and oak are displayed in Figure 9a,b, for the combined data of beech-1 and 2 as well as oak-1 and 2. The objective was to provide a general equation for each species.

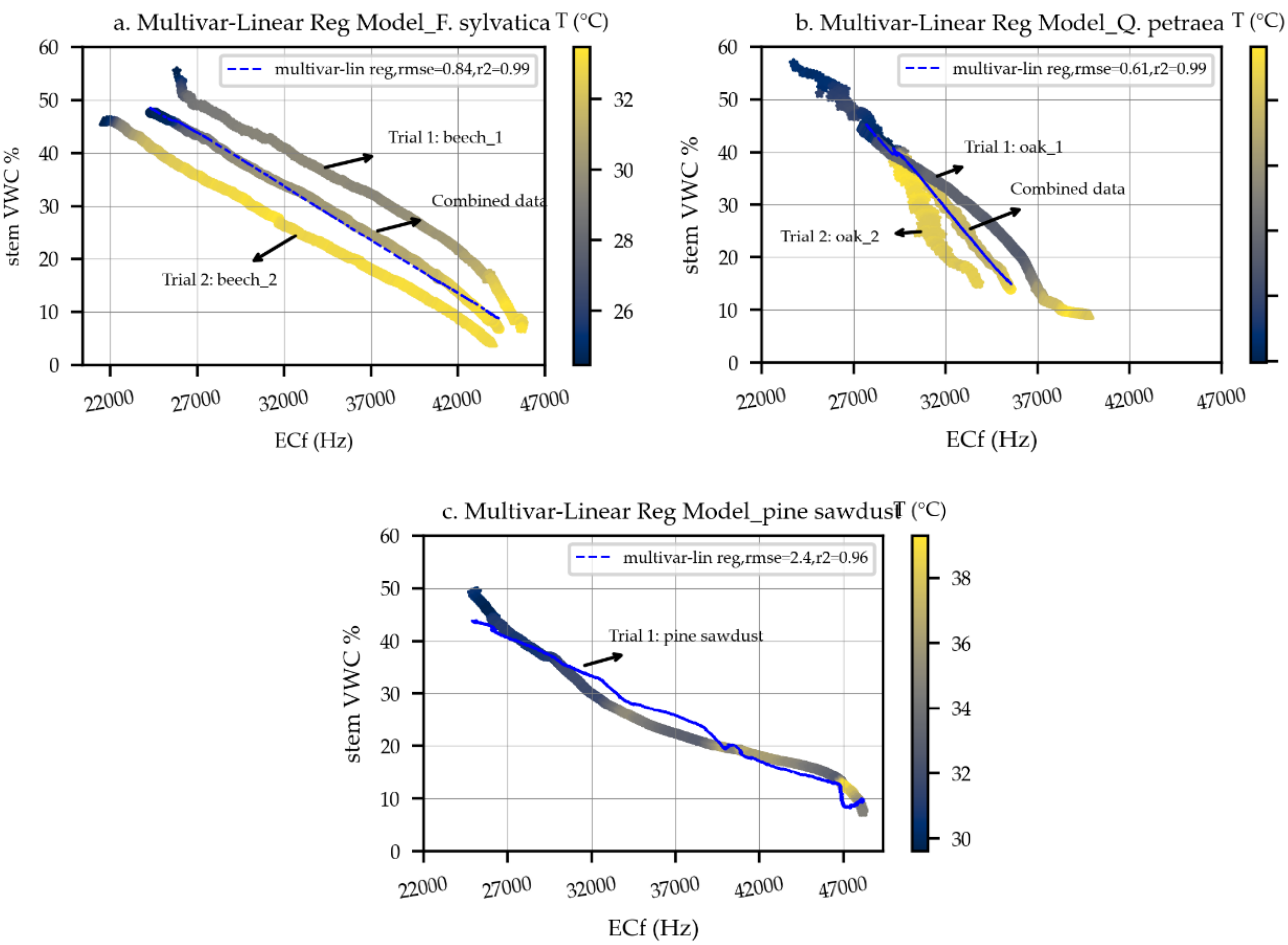

Figure 9. Relationship between Ref probe's output: ECf and sample temperature versus the digital balance output: stem volumetric water content across the selected samples, (**a**) Beech, (**b**) Oak, and (**c**) pine sawdust.

Table 3. Calibration equations to estimate stem volumetric water content for the different samples. Coefficients 'β_0', 'β_1', and 'β_2' are presented for multiple linear equations in the standard form: $stem\ VWC\ (\%) = \beta_0 + \beta_1 \times T + \beta_2 \times ECf$.

Scheme 2	β_1	β_2	β_0	R^2	$p > \|t\|$	RMSE	No. Obs
Beech	−0.23	−0.0021	93	0.996	<0.001	0.86	1430
Oak	−0.56	−0.0042	150	0.996	<0.001	0.61	889
Pine sawdust	−0.61	−0.0013	96	0.969	<0.001	2.4	8263

Therefore, to derive the combined data, we extracted the temperature and *ECf* (Hz) output where the *stem VWC* was equal for both trials.

In Figure 10, the predicted values from the multivariate linear regression model (Table 3) are displayed on the *y*-axis, while the actual values from the dataset are displayed on the *x*-axis. The regression analysis of each substrate demonstrates that the accuracy of the predicted stem VWC data is rather high considering the R-squared and *p*-values (0.996 and <0.001) [64]. However, considering the respective RMSE for each result, both the regression models of beech and oak suggest an acceptable explanation (~RMSE < 0.8) for describing the trends between the predicted and the actual stem VWC data [64]. For the pine sawdust, however, the model reflects a poor ability to predict stem VWC (Table 3).

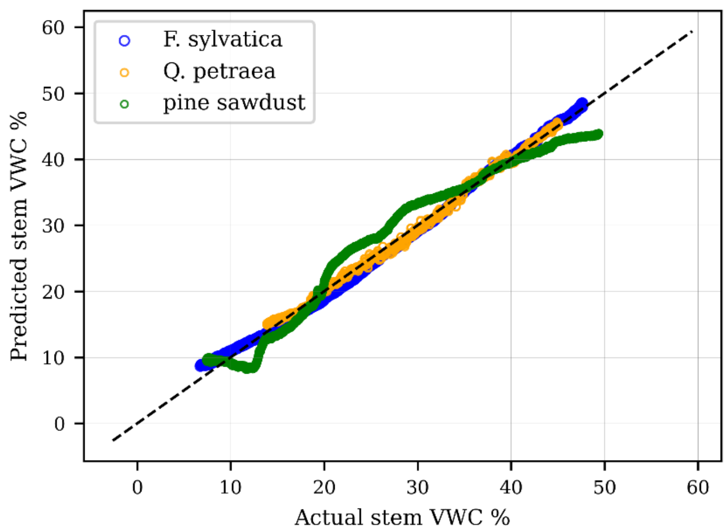

Figure 10. Predicted stem VWC values (multivariate linear regression model output) versus actual stem VWC (digital balance records) for the selected samples.

To conduct species-specific calibration equations, instead of a model of best-fit approach, multiple linear regression was applied to compare the variability of the slope (β_1 and β_2) across the samples. Intraspecies variability was rather limited. However, interspecies variability was more pronounced, especially for those samples collected from the northern sides of the stems. The observed differences in the slope (β_2) between the species can be explained by the differences between the species in terms of the area of living tissue, freely available water in the plant tissue, water molecular bounding condition, water potential, wood anatomical structure (small vs. larger vessels), etc., which is the objective of future research [65]. This result suggests that for the same range of frequency change, oak dries at a rate approximately two times greater or more in comparison with diffuse-porous beech under the same experimental condition. The reported pine sawdust data are here considered only as a reference since they do not compare with real fresh wood samples.

3.1.3. Relative Saturation Index

The measurements and calibrations are highly dependent on the material temperature, moisture level, and variability of species wood anatomy, requiring, therefore, species-specific calibration to be used in field operations.

To address the abovementioned limitations, continuous monitoring and long-term datasets can and should be used to derive a relative index that can represent the stem moisture dynamics of time series data. Having data for one complete growing season which was analyzed and elaborated by applying statistical detection for outliers, anomalies, records caused by the sensor failure, the idea is simply to find the minimum recorded frequency (Hz) and the corresponding stem temperature to mark this point as the saturation point for each individual. Accordingly, the rest of the results will scale up based on the detected saturation point for every single tree. In the current version of TT+, the utilized capacitance sensor has a 50 kHz frequency band; therefore, in the data elaboration, we considered min (≈12,000 Hz) and max (≈50,000) events for the mentioned sensor.

We propose a procedure to derive such an index as outlined in the following. First, the frequency data (ECf) recorded by the Ref probe decreases as the material temperature increases. Second, the local minimum of the frequency reported value occurs at the saturation point and the local maximum occurs while the sensor is exposed to the driest conditions in the living tissue. Taking advantage of these two facts, considering the fiber saturation point for each single living tree in a given period of time, the minimum frequency record and the corresponding stem temperature are required to determine the expected frequency signal, $ECf_{adj}(Hz)$, by the stem temperature effect at the same moisture level.

$$ECf_{adj}(Hz) = m_1 \times (T_i - T_{sat}) + ECf_{sat} \tag{10}$$

where m_1 is the temperature sensitivity slope, T_i is the temperature of the stem in °C, T_{sat} is the stem temperature associated to ECf_{sat} in °C, and ECf_{sat} (Hz) is the minimum raw record of the frequency data in one cycle of the growing season. Here, since the m_1 is referring to the saturation point, the slope of temperature sensitivity for "water" ($-81\ \frac{\Delta Ecf}{\Delta T}$) can be considered.

The relative index of the stem saturation % is given as:

$$\text{Relative stem saturation }\% = \left(1 - \frac{ECf\ (Hz)_i - ECf_{adj}(Hz)}{ECf_{adj}(Hz)}\right) \times 100 \tag{11}$$

where $ECf\ (Hz)_i$ is the current frequency record.

One complete growth season is recommended to accurately capture the above event. Furthermore, to convert the relative stem saturation index to the stem VWC, we suggest using tree-coring techniques to scale up the results. From our observations, the corresponding date and time of Min_{ECf} and Max_{ECf} denote optimal periods to collect physical stem core samples. By following the oven-drying method, the derived minimum and maximum for stem VWC are established, essentially allowing the evaluation of tree stem water content for any reported ECf value for each individual tree.

3.2. Field Results

3.2.1. Individual Variability in Sap Flow Rate and Stem VWC in Beech

Measurements from the installed TreeTalkers in the MOF study area, in species *Fagus sylvatica*, demonstrated the capability of the system to detect individual differences in the hydraulic status of each tree. Three individuals, TT25-TT54-TT62, were selected, giving a snapshot of tree functionality toward stem temperature (Figure 11a), SFD rate (Figure 11b), relative stem saturation (Figure 11c), and stem VWC, using Equation (9)—beech (Figure 11d), in mid-June and mid-September during the vegetation period of 2020.

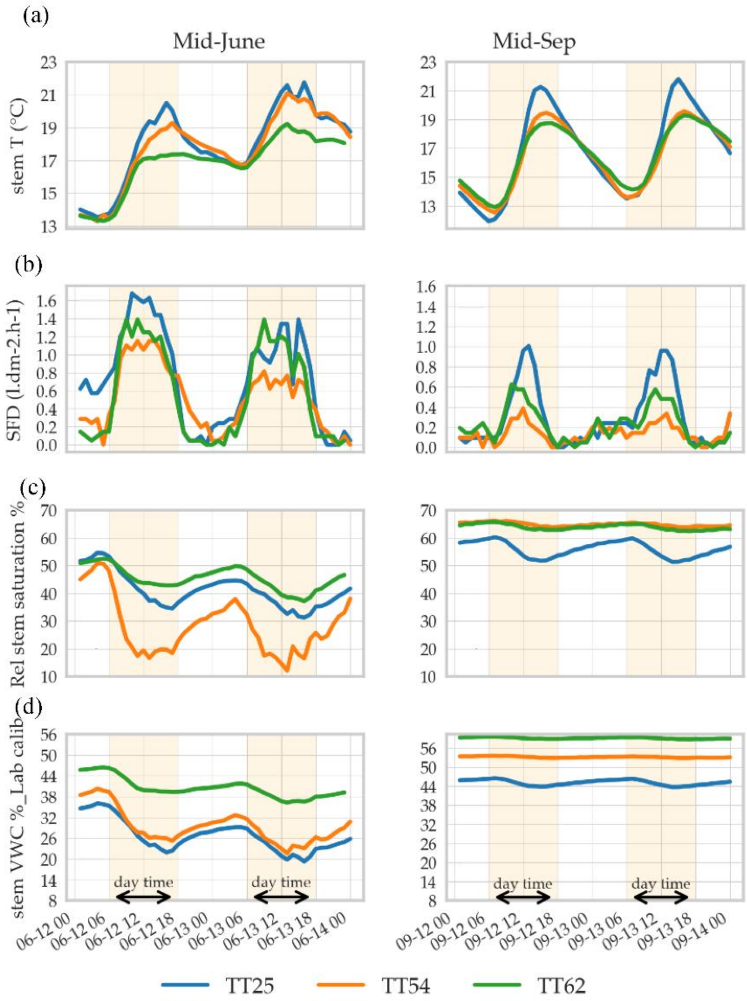

Figure 11. Individual behavior for three selected trees (25, 54, and 62) based on available ancillary data toward (**a**) stem temperature, (**b**) SFD, (**c**) relative stem saturation index, and (**d**) stem volumetric water content, based on TreeTalker hourly data focused on June vs. September 2020.

The variance in the SFD and stem water content in individual trees may be attributed to different parameters such as the DBH size class, sapwood area, canopy volume, etc. For example, TT25, with the lowest canopy volume among the selected trees, has the highest flux rate. Focusing on diurnal and nocturnal patterns for the SFD, we see that the general pattern holds true for each tree; however, the magnitude remains different for each individual, possibly suggesting that individual trees do not demonstrate homogeneous responses to abiotic factors. Indeed, tree cellular structure, hydraulic tissue matrices, physical size, and canopy volume, i.e., leaf area, may be more important factors determining the magnitude and change in flux vs. water storage across these individuals.

Diurnal variations in SFD rates (Figure 11b) versus the stem VWC (Figure 11d) indicate that variation in the SFD rate and stem VWC are not strictly related. For example, TT25, with the highest SFD rate, does not necessarily denote the highest stem VWC. The drivers for this observed phenomenon are linked to two possible scenarios. Firstly, hydraulically, trees with higher facilitation of flux rates, inversely store less water (see Figure 11b,d for TT25) [66–68]. Secondly, water scarcity, tree health, size, factors of competition, and suppression may all contribute to decreased available water for both flux and stem WC, requiring more investigation (see Figure 11b,d for TT54).

3.2.2. Seasonal Rhythm of Stem VWC and Relative Saturation Index

Seasonal variability of stem VWC and the relative saturation index for several trees of beech from the MOF area are shown in Figure 12a,b. Results from Equation (9)—*beech* and Equation (11) appear in Figure 12a,b, respectively. In Figure 12a specifically, hourly fluctuations of stem VWC are recorded for all individuals in the MOF study from June to November 2020, with the rolling average of all individual trees displayed in black color. September, marking the end of the growing season in the MOF, exhibited higher stem VWC than in June. Although precipitation in June (50.8 mm) was even higher than in September (36.4 mm), reduced transpiration to the end of the vegetation period can explain the observed increase in stem VWC and the saturation index [69,70] (Figure 12). For the same reason, the diurnal rhythm is less pronounced in September. Due to a later sunrise in this month and subsequent reduced photoperiod, approximately 1:45 h later than in June, tree transpiration is already reducing in September, and the stem VWC contribution is realized later (between 11:00 and 16:00). Recovery starts immediately after a minimum level is reached and this is coupled with limited photosynthesis confined to a small window of a few hours in the late vegetation period. Temporal shifts match a later sunrise and earlier sunset (Figure 12a,b).

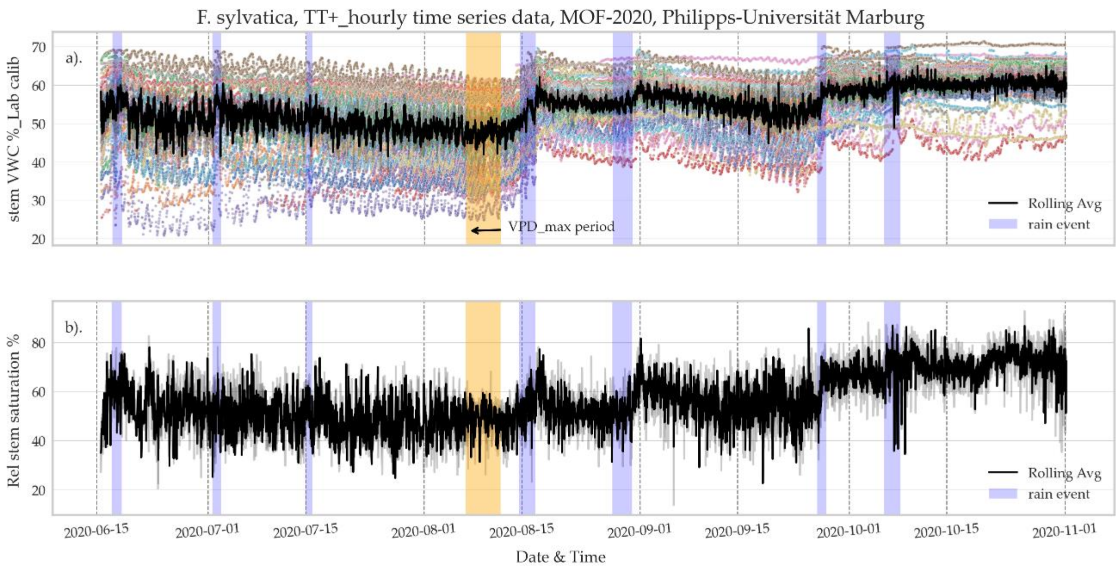

Figure 12. Seasonal variability of (**a**) stem VWC for all individuals (colored points) and combined rolling average using all data (black), (**b**) relative stem saturation index % based on a combined rolling average across all individual data. All data are derived from hourly data by TT+, species *Fagus sylvatica* L. in the MOF study area.

Observed hourly data, captured by the TreeTalker (Figure 12a,b) for one growing season, accurately reveal the impact of elevated temperature and an acute heatwave from 15 July to 15 August 2020 across Germany. Subsequently, a large impact on the trees' water storage level in beech trees was evident (Figure 12a,b) and can be explained by [63,71].

Based on our observations, we see a general population response to abiotic events such as dry periods and rainfall events (see Figure 12a,b for max VPD and rain events). However, at an individual scale, the ecophysiological response to climatic variables varies according to the magnitude (see Figure 12a—colored points). Although general observations are evident, further investigations are required about both population and individual responses to abiotic factors. For instance, the last rainfall event demonstrates a drop in both indices, stem VWC and the stem relative saturation index, which requires a deeper understanding and analysis.

4. Conclusions

This study confirms that TreeTalker can estimate the time evolution of relative changes in stem water content. According to the experimental results, the following conclusions can be drawn:

1. The TreeTalker, having a capacitive sensor, is an effective IoT-based device for real-time and continuous estimation of relative stem saturation at a single tree level, furthermore, demonstrating a reasonable capacity for capturing a single tree's eco-physiological behavior under differing environmental conditions.
2. The application of continuous and simultaneous monitoring of several trees is showing a remarkable coherent response to climate events (rain and drought), where precipitation has a positive impact, with increased stem VWC, and decreases are evident in dry periods.
3. Stem water content varies regularly according to diurnal and nocturnal fluctuation, following the overall trend of rising during the night and falling during the day. This observed trend is coherent with stem recharge and increased transpiration rates are driven by photosynthesis.
4. The accuracy of the sensor, however, seems not yet to be adequate for diurnal trend estimation under small water content variations. We are continuously working on improving the sensor with a high frequency of oscillation (100–500 MHz) to increase the sensitivity to the level requested by daily trends.
5. Individual tree ecophysiological and geometrical characteristics demonstrate a plausible connection to the pattern and amount of stem water content.
6. For further optimization of species-specific calibrations of the Ref probe, we suggest a seasonal sampling campaign to collect wood core samples.

In addition to the above findings, we note that IoT devices such as the 'TreeTalker' are indeed novel, showing multifunctional nested sensor and network capabilities. As such, limitations typically arise through connectivity, whereby terrain, distance, and atmospheric instability may cause signal weakness in remote areas. However, given that TreeTalker has three possible data repositories, these issues are generally overcome. With most new technological exploration, as is the case with the capacitance sensor described in this study, noise from the sensor–environment interaction is plausible and requires both knowledge of the system and in situ calibration. We suggest applying different frequency bands across varied species with suggested in situ calibrations. Therefore, we encourage future research applying the TreeTalker to differing tree species, with the aim to scale up the measurements and explore tree–water interactions under varying dynamic scenarios, both under controlled and field conditions.

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